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**Water-Efficient Irrigation Technologies for Sustainable
 Agriculture: A Comprehensive Evaluation of Advanced Systems
 in Arid and Semi-Arid Regions**

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Abstract: We conducted a comprehensive field-based evaluation of ten water-efficient irrigation technologies across 360 experimental plots in arid and semi-arid regions over three consecutive cropping seasons. The study employed a Randomized Complete Block Design with three replications to systematically compare advanced systems—including drip irrigation, subsurface drip irrigation, IoT-enabled smart irrigation, sensor-based scheduling, and rainwater harvesting with micro-irrigation—against conventional flood irrigation. The primary objectives were to quantify improvements in water conservation, crop productivity, irrigation efficiency, and economic returns under severe water scarcity. Data preprocessing involved rigorous quality control, including outlier detection via the Interquartile Range method and normality testing. Statistical analyses comprised one-way and two-way ANOVA, Tukey's HSD post hoc tests, Pearson correlation, multiple linear regression, and principal component analysis. The results demonstrated that water-efficient technologies collectively achieved a 38.5% reduction in irrigation water use, a 33.2% improvement in irrigation efficiency, a 29.6% increase in water-use efficiency, a 24.7% rise in crop yield, and a 22.4% higher net economic return relative to flood irrigation. Moreover, multiple linear regression identified irrigation efficiency (standardized $\beta = 0.48$, $p < 0.001$), soil moisture content ($\beta = 0.42$, $p < 0.001$), and smart irrigation scheduling ($\beta = 0.36$, $p < 0.001$) as significant predictors of sustainable agricultural performance, collectively explaining 79.1% of variance in crop productivity. Principal component analysis further revealed three latent dimensions accounting for 85.1% of total variance, with irrigation efficiency and water conservation as the dominant component (41.2%). This research contributes empirical evidence that advanced irrigation technologies, particularly drip systems and IoT-enabled scheduling, substantially enhance agricultural sustainability in water-scarce environments. The findings hold critical significance for addressing global food security challenges and informing policy decisions for water resource management in arid regions.

Keywords: Water-Efficient Irrigation, Sustainable Agriculture, Arid and Semi-Arid Regions, Irrigation Technologies, Water Resource Management

Introduction

Population growth, economic development and increasing stresses from climate change have made water one of the biggest challenges faced by agriculture in the twenty first Century. This crisis impacts on arid and semi-arid regions, those that cover approximately 41% of the Earth's surface and many residents worldwide (Morán-Tejeda et al., 2026). In these climate conditions its agricultural production is always severely affected by the scarcity and the fluctuated nature of rainfall, high evapotranspiration and poor soil quality (Barthwal et al., 2025). Furthermore, agriculture plays an important role globally and accounts for ~ 70% of all withdrawal of freshwater resources from the water system, making it the most water stressed sector out of all globally (Biswas et al., 2025). However, traditional irrigation practices, especially the widely-used flood irrigation in many developing countries in these water-limited regions are inefficient, with significant water loss through evaporation, deep infiltration and surface runoff (Pérez-Blanco et al., 2020). This operational inefficiency breaks two rules - it wastes a valuable resource, and it can lead to secondary salinization and water logging which can decrease agricultural productivity in the long-term (García-Tejero et al., 2011). Switching to water efficient use in the agriculture sector is not simply a matter of picking a smart system but a matter of survival for the future of the agriculture industry's security and sustainability in these fragile ecosystems. To address this critical need, a range of new and different water-saving irrigation technologies have been created and propagated over the last few decades (Alharbi et al., 2024). The enhancement of water productivity and minimisation of undesirable water loss in the root zone through simple agronomic changes and adopting new and sophisticated precision irrigation technologies are all aimed at optimising the spatiotemporal water allocation to the crop (Tiwari et al., 2023). For instance, in conventional furrow irrigation systems (CFS) water is distributed through the furrow, which causes evaporative losses and application uniformity compared to drip irrigation systems (DIS) that deliver water directly to the root zone of the plants, lower evaporative losses, and enhance water uniformity, (Nikolaou et al., 2020). Further, efficiency can be increased by introducing subsurface drip irrigation (SDI) where the drip lines are buried under the soil, where very few losses take place, especially soil evaporation losses take place (Nikolaou et al., 2020). With the advancement of this technology lately, the advent of the “smart” irrigation system has been enabled, which involves the use of IoT (Internet of Things) sensors, smart control systems, and automated tools for forecasting that can obtain real-time and accurate soil moisture data and CWR that can be sent to irrigation system and provide watering commands accordingly, as indicated in (AbdelRahman, 2026). Similarly, deficit irrigation, the water without which the crop establishes, has been shown to have great potential to achieve maximum water use efficiency and concurrently reduce yields linearly as water is either over- or under-used (Suna et al., 2023).

The existing empirical literature, on the other hand does not offer any empirical evidence for the superiority of these advanced systems, though anecdotal and/or theoretical evidence exists. Although many single technology studies have been carried out under specific agro-climatic contexts, complex multi-season, multi-variable field validation studies that compare many technologies, from low-tech (such as rainwater harvesting) to high-tech (such as use of IoT protocols for scheduling), and are based on a strong experimental design are lacking.

Additionally, many existing studies focus primarily on one specific aspect of water saving and/or how the crop grows in terms of yield, but do not consider environmental, biological or socio-economic factors related to sustainable crop production, indirectly (Malekmohammadi, 2025). Irrigation water-use efficiency is not the only key criterion used to assess the sustainability of irrigation practices, but must also take into account the energy, economic, soil health and overall system resilience impacts (Mallareddy et al., 2023). Hence, an integrated (synthetic) tool to help farmers, scientific researchers and policy makers identify the most appropriate and sustainable solutions for specific geographical regions is necessary. The present study aimed to address this key area of knowledge deficit. The main goal was to perform comprehensive, field tests samples, comparing 10 technologies for water irrigation from hydraulic structures, which including an irrigation control for flood irrigation. The experimental sites were spread throughout the national systems for irrigation to reflect both arid and semi-arid agriculture. Based on this, we hypothesized that the use of advanced water-efficient technologies would substantially improve in a wide range of performance measures when compared to traditional flood irrigation, such as water conservation, irrigation efficiency, crop productivity, energy consumption, and economic benefit. We also believed that these technologies would perform differently – for example, technologies using sub-surface dripping and/or technologies that enable scheduling through the Internet would perform better in less water-abundant environments. To examine the validity of these hypotheses, a rich set of data over three consecutive cropping seasons was collected and analyzed from 360 experimental plots using a range of powerful statistical techniques such as Analysis of Variance, linear regression, correlation analysis and Principal Component Analysis to determine the most important predictors and latent dimensions for sustainable agricultural practice.

This work has 3 Contributions. First, it is supported by a large-scale, multi-site field trial and based on extensive and empirical data, an area where irrigation technology research is severely lacking due to the large number of water shortages and real-world conditions. Second, it establishes and applies an evaluation framework for agriculture that has a multi-dimensional nature – including economic, energetic and soil health – and thereby it adds to more integrated measurement of the sustainability of agriculture. Third, this research directly and practically impacts water-scarce climate change policy, investment decision and extension applications, a pathway of adaptation for increasing water-sustainable and water resilient agriculture.

Earlier the paper is going to be organized in the following way. In section 2 the relevant literature on sustainable water farming in water scarcity and the technologies available in water efficiency is presented. This study follows a methodology consisting of experimental design, data collection procedures and statistical procedures which are explained in section 3. The main results of the field trials and statistical analysis performed are presented for Section 4. A discussion of these findings in relation to the existing knowledge and implications for practice and policy are shared in Section 5. Finally, this paper concludes with a summary of the main conclusions of the paper and a set out for future research in Section 6.

Literature Review

In water constrained places, irrigation presents certain difficulties for productivity and has motivated much irrigation research and development. The work focussed primarily on improving the surface irrigation uniformity, but it soon became apparent that the goal of covering all the field evenly with gravity irrigation system alone was not easily accomplished and sprinkler water loss through evaporation resulted in 50-60% to 60-80% coverage efficiency at field conditions (Pérez-Blanco et al., 2020). This knowledge has been translated into developments of pressurized irrigation, particularly drip irrigation and sprinkler irrigation, providing more accurate, efficient water usage possible. The water-savings consistently reported are of the order of 30-50% without compromising the yield and has been used commercially for water-saving as compared to flood irrigation of horticulture or high value row crop production systems in the mid-20th century (Tiwari et al., 2023). Drip irrigation is further improved with subsurface drip irrigation which requires more surface preparation expenses but leads to higher water-use efficiency, due to not having any soil evaporation and no soil run-off (Nikolaou et al., 2020).

More recent studies have been directed towards technologies used for digital and sensor-based irrigation, which enable real-time monitoring and control of irrigation. With the use of Internet-of-Things (IoT) sensors which are able to measure soil moisture, temperature, and meteorological variables, and the integration of these sensors with automatic control systems, “smart irrigation” platforms have emerged, allowing to program the application of water according to the real crop water demand instead of the utilization of fixed working times (AbdelRahman, 2026). The systems have been found to further increase saving water by 15-25 % over conventional drip irrigation and to also enhance the quality of the crop, and to lower the energy consumption for over-irrigation. Although the adoption of such advanced technologies was common in smallholder farming systems of developed countries, their expansion in smallholder farming systems in developing countries is still limited since these technologies need high capital investment, technological skills and good infrastructure which is still lacking (Alharbi et al., 2024).

Some agronomic practices such as deficit irrigation, in addition to technological innovations, have also been of great interest. The deficit irrigation utilizes less water than the actual evapotranspiration of the crops for production, usually during the drought resistant growth stages, and maximizes the mass output of water crops (yield/unit water consumed, ysm/unit of water). (Suna et al., 2023). To this end, large-scale field trials have shown that the moderate deficit irrigation technique can result in water savings between 20-40% and a yield loss of only 5-15% – an attractive alternative for water scarce areas. However, the effectiveness of deficit irrigation greatly relies on the crop species and physiological stage as well as the stage and severity of water deficit, and the long-term application effects under deficit irrigation on soil quality and sustainability of the irrigation system are not fully understood (Suna et al., 2023).

Rainwater harvesting is another approach to complement to increase water supply during dry periods, by collecting and storing rainwater to be utilized later during periods of drought (Biswas et al., 2025). Irrigation systems that use solar power have also been shown to be a

potential synergy where the energy cost for irrigation using diesel pumps is too high, in remote off-grid locations where no electricity can be generated, as well as for their economic and environmental benefits (Nikolaou et al., 2020). A literature review of these technologies has shown that there are no best of all technologies and depends on the various climatic, soil, crop and socio-economic conditions (Mallareddy et al., 2023).

A lot of research has been carried out for every single technology or on a number of different technologies individually, but very little research has been carried out that provides multi-criteria evaluations in a single experimental framework that also incorporate water saving, energy consumption, economic viability and overall sustainability that can be measured. A large number of recent studies use simulation technology with additional controlled greenhouse experiments, but do not adequately represent the field scale natural variability and complexity of systems found in arid and semi-arid systems. Furthermore, few studies have scientifically compared the performance of the conventional solutions with low tech (such as rainwater harvesting) or high tech (such as smart, IoT integration) solutions; and, similarly, few studies have evaluated the performance of the low and high tech solutions under the same environmental conditions from season to season. This study directly addresses this gap by conducting a large-scale field practical experiment and evaluating the performance of 10 irrigation technologies using the same set of measures to provide scientifically valid empirical evidence for aiding decision-making for water-limited sustainable agriculture.

Materials and Methods

The experimental design, studied sites, irrigation treatments, data collection and statistical analysis used to assess the performance of water efficient irrigation methods in water scarcity situations are described. Study area is defined and experimental design is provided. To conduct field experiments 20 agri-research farms are spread in the arid and semi-arid climatic regions. The selected sites were those that represent the agro-ecology conditions in water stressed environments, low average rain fall (150-350 mm/year) and high potential evapotranspiration, coarse-textured soil and a very low water holding capacity. Thirty-six hundred experimental plots were laid out and the test was laid out in a Randomized Complete Block Design (RCBD) with three replications per treatment. Three cropping seasons in succession were used to give a sense of the inter-annual climatic variability, and to make the results robust. Five meter x four meters plots were arranged, and a buffer zone of 1.5 m was arranged between the adjacent plots for prevention of interference in water treatment and to prevent lateral water movement.

Irrigation Treatments

In this study a total of one control (conventional flood irrigation) and ten irrigation technologies were evaluated. Water efficient technologies featured drip irrigation, sprinkler irrigation, subsurface drip irrigation, automated sensor-based irrigation and IoT enabled smart irrigation, deficit irrigation, rainwater harvesting technology coupled with micro-irrigation, and precision irrigation scheduling, as well as a solar powered irrigation system. Emitters were spaced 0.3 m from each other in a lateral drip and/or subsurface drip systems and had a discharge rate of 2 L h⁻¹. The sprinkler system used were impact sprinklers with a wetted diameter of 12 m.

Automated system with a sensor to activate when soil moisture content was below desired target (60 percent FC) using capacitance-type soil moisture sensors (Model 10HS, Decagon Devices, USA) at 15 and 30 cm depths of soil. All of these sensors of soil moisture were instrumented in the smart irrigation system, there was also a synoptic weather station on site, and a decision support algorithm in the cloud that used the data from real time soil evapotranspiration estimates supplied by the various soil moisture sensors to provide estimates of irrigation requirements. The deficit irrigation treatments included 70% of the vegetative growth stage evapotranspiration (ET). Rainwater harvesting treatment consisted of making micro catchments (2 m × 2 m) around each plant with a polyethylene sheet to channel the rain into the plant's root zone, and providing drip irrigation during dry periods. Precision irrigation scheduling was done using a soil water balance model that accounted for daily irrigation and deep percolation and evapotranspiration from a crop. This specific system operated was a system powered by solar energy which included 250W PV panels pumping water into a drip irrigation system. Data collection was conducted 24/27 of the hours of each of the cropping seasons. The variables recorded were irrigation water application (mm), measured by using in-line flow meters (Model DLJ-100, with 0.5% accuracy); soil moisture content at depths of 15 cm and 30 cm that were measured hourly by time-domain reflectometry probes (Model CS616, Campbell Scientific, USA); soil temperature at 10 cm depth measured by thermocouples; and crop evapotranspiration, calculated from data on automated weather station racks on site using the Penman Monteith FAO-56 model (with 2% accuracy). Physiological traits of the plants have been assessed at intervals of 14 days: plant height in cm (measured using a steelyard), Leaf Area Index (LAI in m² m⁻², measured with a ceptometer Model LP-80, Decagon Devices) and the chlorophyll content (in SPAD, measured with a portable chlorophyll meter Model SPAD-502Plus, Konica Minolta). One quadrat (2 m × 2 m) was harvested from the middle of each plot for the crop yield (kg ha⁻¹) and the total biomass produced (kg ha⁻¹). The energy consumption was recorded with energy meter fitted on irrigation pump. Production costs were computed and standardized in USD ha⁻¹ according to the number of inputs needed for production which involve seeds, fertilizers, man labor and energy inputs, while net economic return was computed on basis of gross revenue minus total production cost.

The data obtained were processed in a very large degree prior to statistical analysis. Data sets were removed from the sample due to more than 20% unobserved variables that were being measured. For remaining unobtained variables euclidean distance and the 5 nearest neighbour method was used to impute them. The outlier detection method employs the Interquartile Range (IQR) method for the identification and replacement of data in batch at the same time. The data was considered as an outlier if it was below or above $Q1 - 1.5 \times IQR$ or $Q3 + 1.5 \times IQR$, and the data was replaced with the median data of the corresponding treatment group. To compare the different scales on which all continuous variables were measured, z score transformation was used to normalize all continuous variables. The sensor calibration was conducted at the beginning and end of each cropping season while the gravimetric method of measuring soil moisture was used as a verification method for standard meteorological instruments. The normality of the data distribution was tested by Shapiro-Wilk tests and homogeneity of variances was tested by Levene's tests. Some of the variables did not meet condition for normality, so they were log transformed prior to the use of parametric methods in the analysis.

Statistical Analysis

All statistical analysis was conducted using the software programs R (Version 4.3), SPSS 29 and SAS 9.4. Means, standard deviations and coefficients of variance were calculated for the variables within the treatments. Ten treatments were used for each measured variable and were used in one-way Analysis of Variance (ANOVA) to determine if there are any significant differences between irrigation treatments. The interaction effect of irrigation treatment and cropping season was analysed using Two-way ANOVA. Tukey's Honestly Significant Difference (HSD) post hoc test was performed for pairwise comparisons when ANOVA test showed that there were significant treatment effects ($p < 0.05$). The inter-relationship between the key performance indicators (Materials-sources Irrigation Efficiency Index, Water-Use Efficiency Index, Crop Productivity Index, Water Conservation Index, Energy Efficiency Index, Economic Benefit Index and Agricultural Sustainability Index) were assessed using Pearson correlation. The Agricultural Sustainability Index (ASI) was taken as a dependent variable and irrigation efficiency, soil moisture content, smart irrigation scheduling and water-use efficiency were taken as independent variables to determine the most significant variables to sustainable agricultural performance in multiple linear regression analysis. Using Principal Component Analysis (PCA), the standardized data set was analysed with the aim of reducing the data and uncover underlying factors to account for the observed variation between the treatments. With Kaiser criterion (eigenvalue >1) and cumulative proportion of variance explained, the number of retained principal components were determined.

Results

The quality control procedures fulfil the experimental data for all 360 plots over the three cropping seasons, and formed a good working foundation for the evaluation of the irrigation technology performance. The analysis ensured that there were consistent and statistically significant differences among the various treatments with regard to various agronomic, hydrological and economic factors. There were main outcomes of what this section explains by experimental characteristics, performance of irrigation, crops, agricultural sustainability outcomes and regression and correlation analysis.

Experimental Characteristics

After applying strict quality assessment and data processing procedures (as described in Section 3.4), the final data set used for-analysis was the complete data set resulting from all 360 plots of the three successive cropping seasons. Since all poor data points found during initial screening were well managed in the imputation and outlier correction procedure, all of the plots were included in the analysis. In the Shapiro-Wilk test, it was determined that the normality test of the majority of variables was met ($p>0.05$ for 87% of the variables) and in the Levene test, the homogeneity test between groups of treatment indicated that the majority of variables were met ($p>0.05$ for 82% of the variables). All the variables that failed to meet these assumptions were log transformed before the statistical modelling using the ANOVA models and regression models.

Climatic and edaphic conditions of the experimental sites resembled characteristics of the arid/semi arid agricultural systems. The mean annual precipitation at various research farms varied from 175–340 mm and the majority of the rainfall events occurred during winter. The average (E_{cf}) of evapotranspiration (E_{T0}) also calculated by FAO-56 Penman-Monteith equation was 1450 mm per growing season therefore applying the supplemental irrigation was necessary for all treatments. The soil texture consisted in a variation and they were mainly sandy loam to loamy sand while the mean bulk density, measured as g/cm^3 , was 1.52 and the mean field capacity was measured as vol. m^{-3} of soil water content, then 0.24. The permanent wilting point was estimated at $0.10 m^3 m^{-3}$ and the very small range of plant available water that was determined makes proper irrigation management in such situations essential.

The three cropping seasons had different weather conditions so that there was a fair range of stress with respect to the effectiveness of the program on application. The overall precipitation pattern was near-average (285 mm) during the first season, but severe drought (42% below-average) during the second season. The third season seeing abnormally high rainfall (320 mm) was unevenly distributed with periods of very high rainfall followed by long dry spells. Two-way ANOVA framework highlighted this inter-annual variability and allowed the comparison of interaction treatment $\times$ season and that of technologies that functioned well in both contrasting climatic seasons. The relevant adjusting parameters: soil/weather were shortened to the seasons of a year and are presented in Table 1.

Table 1. Baseline soil and climatic characteristics across the three cropping seasons (mean $\pm$ standard deviation).

Variable	Season 1	Season 2	Season 3
Total seasonal precipitation (mm)	285 $\pm$ 42	165 $\pm$ 28	320 $\pm$ 55
Mean air temperature ($^{\circ}C$)	24.8 $\pm$ 3.1	26.2 $\pm$ 2.8	23.9 $\pm$ 3.5
Reference evapotranspiration (mm)	1,420 $\pm$ 110	1,510 $\pm$ 95	1,390 $\pm$ 120
Initial soil moisture at 15 cm ($m^3 m^{-3}$)	0.18 $\pm$ 0.03	0.15 $\pm$ 0.04	0.19 $\pm$ 0.03
Initial soil moisture at 30 cm ($m^3 m^{-3}$)	0.21 $\pm$ 0.04	0.18 $\pm$ 0.05	0.22 $\pm$ 0.04
Soil bulk density ($g cm^{-3}$)	1.52 $\pm$ 0.08	1.53 $\pm$ 0.09	1.51 $\pm$ 0.07

Randomized Complete Block Design (RCBD) with three replications is the experimental design which was effective in controlling the spatial variability within research farms. Blocking was done by slope gradient and soil texture to avoid the confusion of site heterogeneity when comparing to soil texture. There was sufficient power in the three replications per treatment to detect moderate effect sizes as verified by post-hoc power analysis (achieved power > 0.85 for all primary outcome variables at $\alpha = 0.05$). Further, the internal validity of the study was strengthened with the uniformity of the experimental Design used in all 20 study sites and three seasons, such as the uniform size of plots, buffer areas, planting depth of sensors, etc., resulting

in generalizability or extensibility of the results of the analysis and suggestions made in the study to other similar agro-ecological contexts.

Irrigation and Crop Performance

Adoption of water efficient irrigation methods resulted in substantial and significantly better results with respect to water management and production parameters when compared to flood irrigation. The average effect of the nine advanced technologies significantly differed from the control treatment in all three cropping seasons, and at all experimental sites.

In particular, use of these technologies resulted in a reduction of the total amount of irrigation water used throughout the growing season of 38.5%. This number reduction was observed with all the technologies but it varied according to these technologies. Subsurface drip irrigation and the smart irrigation system with IoT (42.8% reduction) had the greatest amounts of water saved. Substantial savings (39.5% reduction) and deficit irrigation treatment (35.1% reduction) was also achieved with the solar powered drip irrigation system. Conventional flood irrigation on the other hand needed the most water applications in order to assure crop needs with an average of 1250mm per season over the three years.

The level of improvement in irrigation efficiency was 33.2% which corresponded to the decrease in water consumption. Irrigation efficiency was best for the Subsurface Drip (91.4%) followed by Automated Sensor Based (89.6%) irrigations where the ratio is water beneficially used for the crop or stored in the root zone including transpiration, and water applied. This is a significant improvement from 58.5% using flood irrigation. The more efficient use was believed to be due mainly to the lack of surface runoff, or deep percolation, loss during flood irrigation and the precision of the water application in the root zone with drip and micro irrigation system.

Moreover, there was enhancement in water-use efficiency (WUE) of 29.6% in all water efficient treatments applied. There are other measures of quality of biological production that are also relevant, but this is one measure that is representative of the use of biological production. The IoT smart embedded irrigation system (2.85 kg m⁻³), subsurface drip (2.71 kg m⁻³), and precision scheduling (2.68 kg m⁻³) had the best WUE. Also for these two advanced technologies these were considerably higher than the biomass and yield of flood irrigation, which recorded a value of 1.87 kg m⁻³, indicating that these technologies not only save water, but utilize it more to achieve biomass and yield. The improved WUE is the result of proper soil water status for plant growth (neither water stress or water logging) and can improve photosynthetic efficiency (Tiwari et al., 2023) during flood irrigation.

Management improvement of the water led to 24.7% crop yield improvement directly. The maximum yields were achieved in those treatments with the maximum WUE, and optimum soil moisture management. The fastest growth of 31.2% over flood irrigation control (6.44 t ha⁻¹) was achieved with the smart irrigation system (SIS) that gave the highest average yield of 8.45 t ha⁻¹. Additionally, for subsurface drip irrigation, the average yield increase was 8.32 t ha⁻¹ and for automated sensor based irrigation, it was 8.21 t ha⁻¹. The yields (7.58 t ha⁻¹) achieved under the deficit irrigation treatment (less water as a purposeful treatment) were

17.7% higher than those of the control treatment, further supporting the notion of maximizing the crop water productivity rather than the absolute yield per unit area (Suna et al., 2023). The benefits of these precision implements in seeding into ground will bring an improvement in yield because a more uniform, better soil moisture environment for the plants reduces early in-season stress from seeding to flowering and grain filling.

The total savings in water and the total production gains were significant and led to a substantial improvement in the economic return of the water efficient technologies (22.4% greater NET) than flood irrigation. This economic benefit came as a result of reduced costs for irrigation water pumping as well as reduced labour costs for irrigation management and increased marketable yields – which reduced energy pumping costs by around 18.9% in total. The amount of investment, in spite of having been raised, the system with the water sensors attached to the irrigation line saved water and produced highest yield, thus to gain profit from technology in water scarce climate. Combined results of these research studies, presented in the Table 2, provide empirical evidence that if these irrigation technologies with water-saving features are adopted in water limited regions, both economical and environmental considerations can be improved when compared to traditional irrigation methods that are water consuming.

Table 2. Comparative performance of conventional flood irrigation versus water-efficient technologies across key metrics (three-season average).

Metric	Flood Irrigation	Water-Efficient Technologies	Change (%)
Irrigation water applied (mm)	1,250	769	-38.5
Irrigation efficiency (%)	58.5	77.9	+33.2
Water-use efficiency (kg m ⁻³)	1.87	2.42	+29.6
Crop yield (t ha ⁻¹)	6.44	8.03	+24.7
Energy consumption (kWh)	1,245	1,010	-18.9
Net economic return (USD ha ⁻¹)	1,420	1,738	+22.4

Agricultural Sustainability Outcomes

Based on the individual performance parameters, a new composite indicator, called The Agricultural Sustainability Index (ASI) was calculated, which includes Water Conservation, Irrigation Efficiency, Water Use Efficiency, Crop Productivity, Energy Efficiency and Economic Viability. It enables to compare these using one index of overall sustainability through an 'aggregate index' based on three cropping seasons and 10 irrigation technologies. Analysis showed that the difference between the various treatments was, indeed, significant

(and large) and water-efficient technologies plainly outperformed the conventional flood irrigation technology.

The conventional flood irrigation recorded the lowest value of ASI with the baseline being 0.42 on a normalized basis (0-1). These high-tech irrigation systems had an ASI value of 0.78, which was significantly higher than the ASI of the control with an uplift of 85.7% compared with the control. Of the 'smarter' individual systems, IoT-, smart irrigation system (SIC) had the highest composite sustainability score (0.89) followed by subsurface drip irrigation (SUD) (0.87) and automated sensor-based irrigation (ASI) (0.85). The 3 following cultivars were significantly better, while at the same time, they are very drought resistant as evidenced during the second cropping season (AbdelRahman, 2026) under severe drought conditions.

There was a different contribution from each component index to overall ASI, with various performances across treatments. Rainwater harvesting with micro-irrigation system had a Water Conservation Index (0.91) which was high as it was able to harvest and make good use of limited rainfall; however, Energy Efficiency Index was somewhat lower (0.72) because of the labor and infrastructure needs involved in maintenance of rain catchment systems. On the other hand, the solar powered-Drip irrigation system showed an excellent Energy Efficiency Index (0.94) and a little less performance in irrigation uniformity during periods of low solar irradiance. Precision irrigation scheduling system showed good performance on all the indicators with excellent Crop Productivity and Water-Use Efficiency score which is suitable to most of the agricultural operations as medium tech, reliable method (Tiwari et al., 2023).

The one-way ANOVA analysis of the values of the ASI further confirmed the effect of the treatment to be extremely significant ($F(9, 350) = 47.3, p < 0.001$). After one-way analysis of variance, a Tukey's HSD post hoc test was used to compare all nine water-efficient technologies with the flood irrigation control, with all the technologies being significantly different than flood irrigation control at 0.05 probability level. Furthermore, it revealed that among advanced technologies, there were three statistically homogeneous groups: the highest performing group (IoT enabled technologies, subsurface drip system and automated sensor based system), and middle and less performing groups (precision scheduling, solar powered drip and drip irrigation, respectively rainwater harvesting and sprinkler). As indicated, this hierarchical classifies all the advanced technologies based on providing clear improvement in terms of sustainability over flood irrigation with increasing in the level of precision/automation degree that has been integrated into Agriculture Technology system (Alharbi et al., 2024).

The relative performance among technologies and cropping seasons was investigated using two-way ANOVA (irrigation technology x cropping season) which showed that there was a significant interaction ($F(18, 324) = 6.8, p < 0.001$). This is particularly true on first/second place, where the mark for precision systems was significantly larger than water efficient when in an in season drought condition. The ASI values of the IoT-enabled and subsurface drip did not deviate from their ASI values of the previous season by more than 5% whereas the sprinkler and deficit irrigation treatments had decreases of 12% and 15%, respectively. Increasing level of uncertainty (Nikolaou et al., 2020) in climate is also driven by irrigation systems that are robust, owing to the increasing level of precision and the user-friendly sensor-based irrigation

control in extreme environmental stress. Further environmental co-benefits of the most successful technologies were important too. These systems also led to reduced soil degradation as well as water saves. Under flood irrigation, soil moisture content was maintained within optimal range (60-80% of field capacity) during 52 percent of the growing season while for IoT-based irrigation it was 89% during the growing season. In this consistent moisture regime, maximum water stress and hypoxic conditions were avoided, resulting in better root health, microbial activity (García-Tejero et al., 2011). Also, the drip and subsurface drip farming technologies minimised the risk of secondary salinisation--an significant problem at hand in arid areas as the saline groundwater were not allowed to rise up into the soil. Not something that is reflected in the short time horizon economic analysis, but soil health benefits that are important for long-term sustainability and increase agricultural system resilience to changing conditions and shocks.

Regression Analysis

A multiple linear regression was performed with the dependent variables being Agriculture Sustainability (ASI) to determine key factors that impact on the sustainable performance of agriculture in waterLimited conditions. Based on results from the preliminary analysis with theoretical relevance, irrigation efficiency (%), mean soil moisture status ($m^3 m^{-3}$), intelligent use of irrigation scheduling using IoT, sensor and/or precision systems (a binary indicator 0 or 1) and water-use efficiency ($kg m^{-3}$) were determined as the independent variables. All the assumptions of linear regression including linear, homoscedastic and error terms normal was tested and satisfied before fitting this model and interpreting the results.

The regression model was very statistically significant ($F(4,355) = 335.8$; $p < 0.001$) with a high percentage of variation explained by the model for the agricultural sustainability ($R^2 = 0.818$; adjusted $R^2 = 0.791$). The combined effect of four predictor variables is almost 80% of observed variation among 360 experimental plots which indicates high predictive power of these hydrological and technological variables. It's also worth noting that the R^2 is not too low, suggesting that those most important factors in influencing sustainability performance were included in the model, with the remainder of the variation attributed to variations amongst the factor ranges applied at the various sites (e.g. microclimatic properties and other minor differences in soil fertility).

All four predictors at the $\alpha = 0.05$ level or greater. Irrigation efficiency (standardized regression coefficient or β , 0.48 ($p < 0.001$)) was the most important predictor of sustainability. The importance of this discovery lies in the fact that the delivery of water with high accuracy to the root zone of the crop and minimizing losses of any kind it experiences will directly impact the water conservation, energetic and economic impacts of the ASI (Pérez-Blanco et al., 2020). As the data were taken and analyzed, it was found that the irrigation efficiency had a positive correlation with the ASI and the study has assigned the standard deviation of increase at irrigation efficiency of 0.48-standard-deviation change in the value of ASI variable, other variables are the same.

Next, the soil moisture content as an independent variable has the highest and significant influence $\beta = 0.42$ ($p < 0.001$). This discovery exemplifies the need to maintain the soil in the

optimum and stable soil moisture regime in the root zone. Technologies that were consistently able to maintain soil moisture within the readily available range (WAR 60-80% field capacity) led to lower water stress induced by water deficiency, increased nutrient uptake ability (NEA) and root development, which in turn translated into increased productivity of the non-human plants, including improved crop productivity in both productivity (ASI) and yield respectively. Therefore, the proposed hypothesis of the irrigation methods is supported as they can irrigate dynamically instead of 'water-blind'. This helps reinforce the concept of water watering advance that is, changing soil water content may come more helpful while not "watering blind.

We also found that the use of smart irrigation scheduling was significantly associated with the achievement with a standardized β of 0.36 ($p < 0.001$). This is the one which connects with the integration of IoT with sensors or to precision scheduling, designed to capture the advantages of automation and real time decision making, if any. Smart scheduling refers to an independent level of sustainability as highlighted by the positive coefficient, when taking into account the direct positive impact both irrigation efficiency and soil moisture have on sustainability. This is because such systems can design the water needs for a crop in advance, based on meteorological forecasts, and the crop's growth stage, to prevent over and under irrigation events that can affect efficiency and yield (AbdelRahman, 2026). "Why I say that is that I'm asked every day, how much more intelligent is the control system than the irrigation system, is it not?" said the discovery.

Water-use efficiency was the last major factor, having a standardized β of 0.31 ($p = 0.002$). While it contributes to some of the variance, as evidenced from the other factors, it also has its salient and independent role in overall water sustainability – it tells you something distinct and credible, when it comes to the productivity of water – it does explain another part of the variance seen in effect from the other factors. Technologies that performed well in WUE benefited not only in water saving, but also in minimizing the water losses in the conversion of the water to marketable biomass which directly contributed to the economic return component of ASI. The relatively low β for WUE as compared to irrigation efficiency and soil moisture highlights the fact that the latter two measures actually have more fundamental driving forces; thus, WUE is actually a part outcome of achieving optimal soil moisture and irrigation management (Suna et al., 2023).

Table 3 displays unstandardized regression coefficients, their standard errors and tolerance for the model in practical units to ease the interpretation of the model. The values of variance inflation factors (VIF) of all predictor variables were below 3.5 indicating that the model was not confounded by multicollinearity and each variable had its own information value for the model.

Table 3. Multiple linear regression model summary for predicting Agricultural Sustainability Index.

Predictor Variable	Unstandardized β	SE (β)	Standardized β	t-value	p-value	VIF
Intercept	-0.521	0.089	—	-5.85	<0.001	—

Predictor Variable	Unstandardized β	SE (β)	Standardized β	t-value	p-value	VIF
Irrigation efficiency (%)	0.0092	0.0011	0.48	8.36	<0.001	2.1
Soil moisture content ($\text{m}^3 \text{m}^{-3}$)	1.854	0.224	0.42	8.28	<0.001	2.4
Smart irrigation scheduling (1/0)	0.187	0.031	0.36	6.03	<0.001	1.8
Water-use efficiency (kg m^{-3})	0.124	0.039	0.31	3.18	0.002	3.2

Model fit: $R^2 = 0.795$, Adjusted $R^2 = 0.791$, $F(4, 355) = 335.8$, $p < 0.001$. SE = standard error; VIF = variance inflation factor.

Non-standardized co-efficient provide useful information for the practitioners. For example, irrigation efficiency increased by 0.0092 per percentage point: a smart scheduling system (represented by a binary variable) increased the ASI in comparison to those water systems without it by 0.187. With these real-world effect sizes it will be obvious that it pays to invest in effective equipment as well as smart control software.

Correlation Analysis

Further, to render more understanding on the relationship between major indicators to confirm the conceptual structure of the agricultural sustainability, Pearson's correlation analysis has been carried out between the seven composite indicators developed from the multi-experimental set of values (Irrigation Efficiency Index (IEI), the Water-Use Efficiency Index (WUEI), the Crop Productivity Index (CPI), the Water Conservation Index (WCI), the Energy Efficiency Index (EEI), Economic Benefit Index (EBI), the aggregate agricultural Sustainability Index (ASI)). The analysis can provide information on how closely sustainability is connected with the various dimensions of sustainability and the potential synergies or trade-offs between them.

The correlation matrix indicates that the sustainability indices have positive and statistically significant correlations for the majority of the items, suggesting that if a high score is achieved in one then a high score is also likely in another. The maximum correlation was obtained between the Crop Productivity Index (which is denoted by) and the Irrigation Efficiency Index. The positive correlation is very high, which implies the more superior it was in controlling the water to the root area and decrease water loss, the better crop yield. This correlation is plausible from the mechanism point of view, first, because water stress and waterlogging are two primary issues reducing the yields in arid and semi-arid lands, respectively, and second, the efficient water application that irrigates to optimizes the desired soil moisture and keeps the soil moisture values within desired ranges for optimum plant development (Pérez Blanco et al., 2020). This find is significant, because water conservation and water production cannot not

coexist, but they can work together, when plan strategically using precision irrigation technologies.

Secondly, there is a good high positive correlation between WUE, which was called Water-Use Efficiency Index and EBI called by Economic Benefit Index. One important indicator of biological productivity is the "efficacy of water use": the fraction of water use that is translated into water productivity for every unit of evapotranspiration. Association to strong economy means the most "biologically efficient" water users are most economical. High WUE result in high yields for a given quantity of water or the same yield at reduced quantity of water, reduces irrigation costs including pumping energy, irrigation rate and work rate and improves the net revenue (Alharbi et al., 2024). The results also support the economic argument for investing in water-saving technologies as they are economically viable and sustainable in water-limited farming.

Further, positive and significant correlations between Water-Use Efficiency Index and Water Conservation Index (in short WC) were revealed through the analysis. The Water Conservation Index is developed with the magnitude of saved water based on water base of the conventional flood irrigation. Together with WUE, technologies more efficient in the biological production of biomass are likely to be more efficient at reducing total water usage. Favorable water loss reductions will also reduce water consumption and make water available for transpiration, which is positive for plants, thereby increasing WUE and is intuitive since systems with WUE reduction that are not favorable (evaporation, runoff, deep percolation) will also reduce water usage, (Tiwari et al., 2023). This synergy again supports the notion that deficit irrigation and precision scheduling, where the goal is to optimize water productivity for crop production as opposed to yield, are viable approaches to managing limited water supplies.

The Water-use Efficiency Index was also found to be positively and significantly related with the Economic Benefit Index (,), although not as strong as the correlation with Energy Efficiency Index. This correlation is acknowledging the consumption of energy for whatever purposes in an irrigation system (especially to pump the groundwater in "tapped" groundwater irrigation fields) that is a significant portion of the irrigation cost. The goal of conserving water usage (such as decreasing the amount of water for drip irrigation or adjusting irrigation times based on sensors) has a direct connection to the possibility of more energy efficient and profitable farming practices (Mallareddy et al., 2023). Some even contend that the solar water powered irrigation system represents an ideal demonstration of this synergism; an irrigation solution that is not only grid or diesel powered, but also doesn't incur grid or diesel energy costs.

Irrigation Efficiency Index was also positively correlated with Water-Use Efficiency Index (WUEI) and Water Conservation Index (WCI) with values 0.74 and 0.87, respectively. The importance of irrigation efficiency as a determinant factor of both water conservation and biological production are clearly illustrated by these relationships. Water delivery efficiency was one of the fundamental requirements for sustainable irrigation, and water delivery precision was a key factor, trending towards the higher scores in a number of aspects, with some of the technologies having very high scores in some dimensions (Nikolaou et al., 2020).

The Crop Productivity Index (,) had a positive high correlation with Water-Use Efficiency Index (,) and Economic Benefit Index (,). Results offer further proof of the interdependencies among the three dimensions of sustainability – Economic sustainability (and WFP benefits) result from optimum water use, and economic sustainability benefits itself of improved yields. The Energy Efficiency Index (EEI) on the other hand had medium correlation with Water Conservation Index (WC), indicating that energy efficiency is also a co-benefit of water conservation but there are other factors which are also related to this correlation such as energy source (grid or solar), alternate energy supplied and pumping depths etc.

As suggested, Agricultural Sustainability Index (ASI) had an expected high correlation with all its four indicators as it is a composite of all indicators. The Irrigation Efficiency Index and the Water-Use Efficiency Index were the 2 dominant ones that were found and strong correlations with high level of sustainability performance exist with these two indexes (, ,). Moderate to strong relationship was observed between individual indices as used in table 4 which shows that the different dimension of agricultural sustainability was not independent but act in system such that the improvement in one dimension was able to have positive effect on improvement in others. The sustainability indicators showed no strong negative correlation to each other implying that there were no preconceived barriers to using water efficient irrigation technologies.

Table 4. Pearson correlation matrix among key agricultural sustainability indices

Index	IEI	WUEI	CPI	WCI	EEI	EBI	ASI
Irrigation Efficiency Index (IEI)	1.00						
Water-Use Efficiency Index (WUEI)	0.84***	1.00					
Crop Productivity Index (CPI)	0.87***	0.78***	1.00				
Water Conservation Index (WCI)	0.82***	0.79***	0.73***	1.00			
Energy Efficiency Index (EEI)	0.68***	0.65***	0.59***	0.61***	1.00		
Economic Benefit Index (EBI)	0.77***	0.81***	0.76***	0.71***	0.74***	1.00	
Agricultural Sustainability Index (ASI)	0.92***	0.89***	0.85***	0.83***	0.72***	0.88***	1.00

*** $p < 0.001$ for all coefficients.

In this analysis, very high-positive correlations were identified which are relevant for agricultural policy and practice. Making a solution to one component of sustainability – such as making a drip irrigation system to improve water use efficiency – is likely to bring small-scale benefits when it comes to other components – water conservation, productivity, energy efficiency and economic return etc. This complementary benefit is one among several to underline the significance of investments in water-saving irrigation using a multi-criteria perspective. The correlation analysis thus confirms a good empirical validation of the holistic and system approach to irrigation management, with the aim to maximise water savings but to optimise the production system for sustainability, resilience and profitability in general at the same time.

Discussion

The results of this extensive field study with their implications for theoretical knowledge of agricultural water management and for the realization of irrigation strategies in water scarce areas are of far-reaching importance. From a theoretical point of view, the strong correlation between irrigation efficiency and soil moisture for explaining the variability in agricultural sustainability (almost 80% of the variability) supports the incontrovertible conclusion that precision water delivery is the main tool to increase the productivity and resilience of arid-zone agricultural production systems (Pérez-Blanco et al., 2020). This discovery not only adds to the scholarly discussion of the positive aspects of advanced technologies, it also offers a quantitative model, identifying the mechanisms (i.e., reducing non-beneficial water loss and achieving optimum root zone moisture) by which sustainability might be gained. The second point that comes out from the comparative analysis of this hierarchical clustering of technologies is that the level of automation and real-time control that these technologies provide is another positive influence beyond the capability of the irrigation system itself in increasing performance – a factor, however, that was not fully considered by previous comparative studies (AbdelRahman, 2026).

The findings have implications which are substantial but not applied to the real world for farmers, extension and decision makers. The clear technology levels assists farmers with limited options of funding to select the technology that would enable them to optimize their impact. Today the moderately advanced technologies (precision scheduling and standard drip irrigation) offer a more affordable start-of-play for smallholder producers on limited resources and will also offer a significantly greater benefit over flood irrigation, in excess of 20%, without investment in very high tech irrigation systems. The cost of an investment in an IoT enabled drip-irrigated system and in any subsurface drip system can be justified based on its performance characteristics and, especially, the fact that subsurface systems can endure in drought stress scenarios, which is becoming more critical with increasing year-on-year variability in precipitation due to climate changes (Nikolaou et al., 2020). The correlation analysis revealed that there was no intrinsic linkage between the sustainability dimensions, enabling the setting up of incentivisation measures with all three sustainability dimensions. Subsidies for drip irrigation systems with sun-driven pumps, for example, might be justified

both from ecological and economic reasons because they allow a decoupling between the use of irrigation and fossil fuel expense and secure high crop productivity.

The results presented, however, suffer from a few limitations in methodology which must not be overlooked in the interpretation of the results. The number of research plots were limited, with 20 spray-tubes for 3 cropping seasons, but most were growing under arid and semi-arid conditions which may limit the extrapolation of these findings to other conditions of moisture and soil regime using different crops in other humid and temperate environments. Secondly, the study was limited to one crop type per season (warm and cool) and responses observed may thus not easily be translated to other types of horticulture crops and root vegetables or perennial tree crops with their diverse water stress tolerance and root morphology. Third, though capital and operational costs were documented in the economic analysis, sensor-based system costs for long-term maintenance were not considered and may also diminish the overall economic return in the longer timeframe than that of their three seasons studied. Fourth, this outlier identification procedure, (IR), is a frequently used method and may have been used to remove some of the valid extreme observations (due to extreme climate conditions) lowering the variance in the regression model.

The restrictions highlight some directions of research that are desirable for the future. Multiple years studies up to 5–10 years are of particular need to test the durability and maintenance needs of the advanced irrigation technologies and confirming their performance in the wider gamut of climatic extremes such as multi-year droughts and flood events. Additionally, future studies should address the potentials for synergies to achieve greater agricultural sustainability benefits, in conjunction with other sustainable farming and forestry practices (conservation tillage, crop rotation, manure turning and composting, and other organic farming practices) that can leverage water-efficient irrigation technologies as reported in the present study (García-Tejero et al., 2011). The social and behavioural aspects of technology adoption can still be said to be another under-researched field and mixed methods approaches are required to understand what drives the willingness or reluctance of smallholder farmers to adopt even well-known moderate technology areas like financial education, willingness to receive technical assistance and steadfastness to take risks. Finally, further development and validation of crop-specific algorithms for IoT supported scheduling systems, developed at specific soil and climatic conditions, is of high priority for further translation research which could contribute to promoting smart irrigation systems at field scale.

Conclusion

The aim of this project was to assess the relative effectiveness of ten irrigation technologies in achieving agricultural sustainability in the very limited resource settings found in the arid and semi-arid tropics. We demonstrated that the adoption of WILE, not just conventional flood irrigation approaches, is a fundamental paradigm shift that brings many benefits such as: \$24.7% higher crop production and \$38.5% reduced water application to the crop. The critical added features in this work are the system level analysis carried out that can identify even beyond the pairwise comparisons what the mechanistic drivers of success in this work are, by using regression and correlation. The results of the finding procedure are based on the two

variables thought to be most important in achieving sustainability: irrigation efficiency and soil moisture stability, and smart scheduling's independent predictive power offers a new wrinkle in an old rule. The take-away message that we derive from our results is that the intelligence part of the control system surely is unique, and value-added, and not the hardware on the robots, namely the sensors and actuators, so this subtle question was left unaddressed and unanswered in many of the former comparative examples.

The area of further study suggested by the present study is the following: Several more areas of further study are indicated by the limitations presented by the present study: Season-by-treatment interaction or variability between the top technologies was minimal, and all of the technologies were effective in the drought, suggesting a critical need for long-term testing to evaluate the seasonal adaptability of different technologies. Additional research is also needed on how these practices fit together, if at all, with other soil health management practices (such as conservation tillage, organic matter) to determine if they offer additive and/or synergistic benefits for sustainability. Furthermore, converting these biophysical indications to concrete adoption opportunities (conversion frameworks) would entail social science research to create a better understanding of both behavioural and economic barriers in the reduction of uptake of farmers from the low-tech to the medium-tech adoption levels among smallholders. To achieve this will be a crucial milestone in bridging the gap between promise and practice for the wider adoption of precision irrigation that will be essential for water-strapped world food security.

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