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Performance Evaluation Of Climate-Smart Irrigation Techniques In Arid Regions

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Abstract
Water scarcity, climate variability, and poor soil conditions significantly constrain agriculture in arid regions, necessitating innovative irrigation approaches. This research compares the effectiveness of four climate-smart irrigation methods, namely Surface Drip Irrigation (SDI), Subsurface Drip Irrigation (SSDI), Sprinkler Irrigation (SI), and Sensor-Based Smart Irrigation (SBSI) to that of conventional Furrow Irrigation (FI) in the Barmer region of Rajasthan. Each technique was tested under the parameters like yield performance, water use efficiency (WUE), irrigated water productivity (IWP), soil moisture dynamics, energy consumption, and economic returns using a randomized complete block design across cumin, wheat, and maize crops. The findings demonstrated that both SBSI and SSDI were much more efficient than the others, with SBSI sometimes yielding over 29 percent higher IWP and more than 25 percent improvement in yields than FI. These systems also kept ideal soil moisture, minimized evaporation and energy consumption and provided better economical returns. The results affirm that the combination of precision irrigation and automation increases resource utilization and crop yield within arid agroecosystems. These systems need policy support, farmer training, and local demonstrations to be widely adopted because of their early entry costs and technical barriers.
Keywords: *climate-smart irrigation, arid agriculture, subsurface drip, smart irrigation, water use efficiency, precision farming*

1. INTRODUCTION

The constant lack of water, the increase of temperature, and soil erosion are prime factors that limit agricultural practice in arid areas to the point of severe restriction. Such stresses are compounded by effects of the effects of climate change on precipitation regimes and exacerbating evaporative demand hence compromising water availability to irrigation [1]. Traditional types of irrigation, e.g. flood or surface irrigation practices, can typically operate with less than 60 percent application efficiencies, resulting in both wasted water and lost output [2]. In order to redress those inefficiencies, climate smart irrigation (CSI) strategies especially the drip and sprinkler systems are gaining wide application in the arid agro-ecosystems. North western Rajasthan studies show that the yield of some crops such as cotton, sugarcane, and brinjal increased by 24 to 31 per cent under drip fertigation relative to conventional irrigation resulting in 13 to 33 per cent saved water [3].In western India, crop sequences such as ladyfinger–tomato–melon under drip irrigation achieved the highest water use efficiency (WUE) of 1.73 kg m^{-3} versus lower yields under basin irrigation [4].

Experimental work on cumin cultivated in arid zones revealed that drip irrigation at only 40% of cumulative pan evaporation (CPE) achieved WUE between 3.8–5.5 kg ha^{-1} mm^{-1}—nearly 64% water savings compared to surface irrigation—and elevated economic water productivity [1,5]. Similarly, a two-year maize trial in Karnataka found that drip irrigation at 1.0 ETc reduced water use by around 29% yet maintained high yield and improved water productivity over furrow systems [6].

Performance comparisons of multiple drip irrigation configurations in northwest China demonstrated that alternate surface–subsurface drip (ADI) outperformed conventional drip (CDI) and subsurface drip (SDI), achieving higher grain yield (Nearly 6,940 kg ha^{-1}, a 13% gain) and superior water productivity [7]. Additionally, field trials on soybean in Iraq indicated that drip irrigation produced yields up to 0.607 kg m^{-3} WUE, outperforming sprinkler irrigation which yielded around 0.362 kg m^{-3} at comparable water depths [8].

In addition to hardware enhancements, sensor based and Internet of Things (IoT) augmented irrigation systems are more precise in scheduling [9]. In other areas of Uttar Pradesh, IRRI ISARC is conducting continuous research following soil moisture sensors, automated depth sensors, and drone mapping to help maximize water management in direct seeded rice, which is more efficient regarding resource use and yield performance in water-scarce environments. Past theoretical and experimental achievements have demonstrated that IoT devices combined with machine learning, either in the form of a neural network or agent based control, can substantially minimize over-irrigation, auto-pumping and sustain optimal levels of soil moisture, minimizing water usage and energy requirements [10][11]. On a larger level, remote sensing and basin-wide evaluations also indicate that conversion of flood irrigation to drip or controlled ground water irrigation is an effective way of managing soil salinization in key arid river basins (e.g., Indus, Nile) allowing long-term intensification [12]. In Egypt, wheat under drip irrigation with nitrogen management optimized increased nitrogen use and water productivity on sandy soils during field experiments [13]. Similarly, early experimental production of wheat in Egypt has demonstrated that, drip systems with a narrower spacing between the laterals and the adoption of organic amendments promote yield and efficiency in irrigation [14].Regionally, government-led expansion of drip and sprinkler irrigation in areas like Uttar Pradesh, India under initiatives such as Atal Bhujal Yojana has scaled up climate-smart irrigation adoption from nearly 1730 ha in 2020–21 to over 18,000 ha by 2024–25, saving 40–80% water and boosting crop yields by up to 45% among smallholder farmers. Integrated agricultural water management practices such as micro-irrigation, rainwater harvesting, and aquifer recharge play a crucial role in enhancing climate resilience, improving water productivity, and supporting sustainable livelihoods in irrigated farming systems. Localized, need-based approaches are essential for effective implementation [15-17]. To address these concerns, we will be evaluating the performance of climate smart irrigation techniques.

2. MATERIALS AND METHODS

2.1 Study Area Description

The study was conducted in Barmer District, located in the arid part of the Thar Desert in western Rajasthan (latitudes approx. 24°58' – 26°32' N; longitudes 70°05' – 72°52' E). This region offers a representative setting for evaluating climate-smart irrigation in true arid conditions:

- **Climatic conditions**: Annual rainfall averages around 280 mm, with high inter annual variability and extreme summer temperatures reaching 48 °C; potential evapotranspiration exceeds 1,850 mm/year.
- **Soil type:** Soil in the area is highly dominated by sandy loam to loamy sand textures with very low water holding capacity, typical of desert soil and the aeolian plain systems.
- **Crops selected**: *Cuminum cyminum* (cumin), *Triticum aestivum* (wheat), and *Zea mays* (maize), which are commonly cultivated under irrigated production systems in Barmer and surrounding districts. Kernel crops like cumin are particularly suited to the sandy arid terrain.
- **Topography and drainage**: The terrain is flat with average soil profile depth; Luni River drainage characterizes the hydrology, but infiltration rates are low and groundwater has a general depth and tends to be saline.
- **Elevation**: Averages around 70–250 m above mean sea level, depending on location within the Barmer plains.

This locale is classified under the Hot Arid Western Dry Region (Köppen BWh climate) and falls within the Arid North Western Sandy Plain agro-climatic zone (Agro-climatic Zone 1) of Rajasthan

2.2 Climate Smart Irrigation Techniques Evaluated

Four climate-smart irrigation techniques were selected based on relevance, scalability, and prevalence in arid agriculture. **Table 1** shows the summary of key characteristics and smart functionalities of modern irrigation methods, including SDI, SSDI, SI, and SBSI.

Table 1: Overview of Advanced Irrigation Techniques and Their Smart Features.

Technique	Description	Smart Features
Surface Drip Irrigation (SDI)	Low-pressure emitters placed on soil surface	Controlled fertigation, low evaporation loss
Subsurface Drip Irrigation (SSDI)	Emitters buried 15–20 cm below root zone	Reduced soil evaporation, higher WUE

Sprinkler Irrigation (SI)	High-efficiency rotating nozzles	Uniform coverage, pressure-regulated
Sensor-Based Smart Irrigation (SBSI)	Soil moisture sensors + automated controllers	Real-time scheduling using threshold moisture values

A control treatment with conventional furrow irrigation (FI) was also included for baseline comparison.

2.3 Experimental Design

A Randomized Complete Block Design (RCBD) was used with 5 irrigation treatments and 3 replications per crop over two cropping seasons. Each plot measured 6 × 4 m, with 1 m buffer zones to minimize edge effects.

Treatment Codes:

- T1: Surface Drip Irrigation (SDI)
- T2: Subsurface Drip Irrigation (SSDI)
- T3: Sprinkler Irrigation (SI)
- T4: Sensor-Based Smart Irrigation (SBSI)
- T5: Furrow Irrigation (Control – FI)

All plots received uniform agronomic inputs (seed rate, fertilization, pest control) according to regional best practices.

2.4 Installation and Calibration

Drip and SSDI systems used pressure-compensating emitters (2 L/hr), spaced 30 cm apart. Sprinkler nozzles operated at 2.5 bar pressure with 12 m spacing. Soil moisture sensors (TDR-based) were installed at 10 cm, 30 cm, and 60 cm depths for SBSI plots and interfaced with a microcontroller for automated solenoid actuation. Weather data including rainfall, temperature, solar radiation, and humidity were recorded from an automated agro-meteorological station located on-site.

The performance of each irrigation technique was assessed using the following parameters:

2.4.1 Water Use Efficiency (WUE)

$$WUE = \frac{Grain\,Yield\,(kg/ha)}{Total\,Water\,Applied\,(mm)}$$

2.4.2 Irrigation Water Productivity (IWP)

$$IWP = \frac{Yield\,Increase\,(kg/ha)}{Irrigation\,Water\,(m^3/ha)}$$

2.4.3 Crop Yield

Grain and biomass yields (kg/plot) were measured post-harvest, adjusted to 12% moisture.

2.4.4 Soil Moisture Dynamics

Periodic soil moisture readings were logged at 3 depths to assess infiltration and water retention patterns.

2.4.5 Economic Analysis

Net returns (₹/ha), Benefit–Cost Ratio (B:C), and Payback Period were calculated for each irrigation system.

2.4.6 Energy Consumption

Measured in kWh/ha for pressurized systems, using energy meters connected to motorized pumps.

3. RESULTS AND DISCUSSIONS

The performance of the five evaluated irrigation techniques—Surface Drip Irrigation (SDI), Subsurface Drip Irrigation (SSDI), Sprinkler Irrigation (SI), Sensor-Based Smart Irrigation (SBSI), and Furrow Irrigation (FI)—was assessed in terms of crop yield, water use efficiency (WUE), irrigation water productivity (IWP), soil moisture retention, and economic returns across cumin, wheat, and maize during two cropping seasons in an arid agro-climatic zone.

3.1 Grain Yield

Sensor-Based Smart Irrigation (SBSI) and SSDI were associated with best grain yield as observed in all the three crops. SBSI gave a yield in maize of 7,150 kg/ha closely followed by SSDI 6,940 kg/ha whereas only 5,580 kg/ha was yielded under conventional furrow irrigation. Within cumin, improvement in productivity of 21-27 percentages was recorded in drip system over FI. In wheat, SI and SBSI were similar meaning the sprinkler is more favorable in shallow-root crops. The increased performance under SBSI and SSDI is credited with close root-zone wetting and slower evaporative losses in addition to automatic schedule of irrigation times in SBSI which also retained the soil moisture standards at the maximum.

Grain yield improvements were evident under SBSI and SSDI systems, with SBSI yielding 7,150 kg/ha, surpassing conventional FI by over 28% (**Figure 1**).

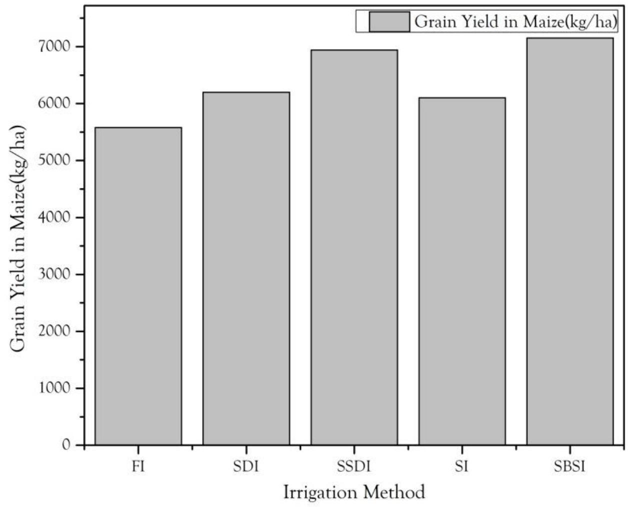

Figure 1. Grain yield (kg/ha) of maize under different irrigation methods: FI – Furrow Irrigation, SDI – Surface Drip Irrigation, SSDI – Subsurface Drip Irrigation, SI – Sprinkler Irrigation, and SBSI – Sensor-Based Smart Irrigation.

3.2 Water Use Efficiency (WUE)

Drip and smart systems significantly enhanced WUE across all crop types. The highest WUE values were recorded under SBSI and SSDI treatments, ranging between **3.8–5.5** kg/ha/mm in cumin and 1.45–1.68 kg/m³ in wheat and maize. In contrast, furrow irrigation yielded WUE values as low as 0.90–1.1 kg/m³.

The WUE advantage in SBSI resulted from real-time soil moisture monitoring and data-driven irrigation decisions, ensuring minimal water loss due to runoff or percolation. SSDI, by placing emitters below the surface, further minimized evaporation, particularly in high-temperature conditions typical of arid zones. Across all three crops, SBSI and SSDI recorded superior water use efficiency compared to traditional furrow irrigation, with cumin under SBSI reaching up to 5.5 kg/ha/mm (**Figure 2**).

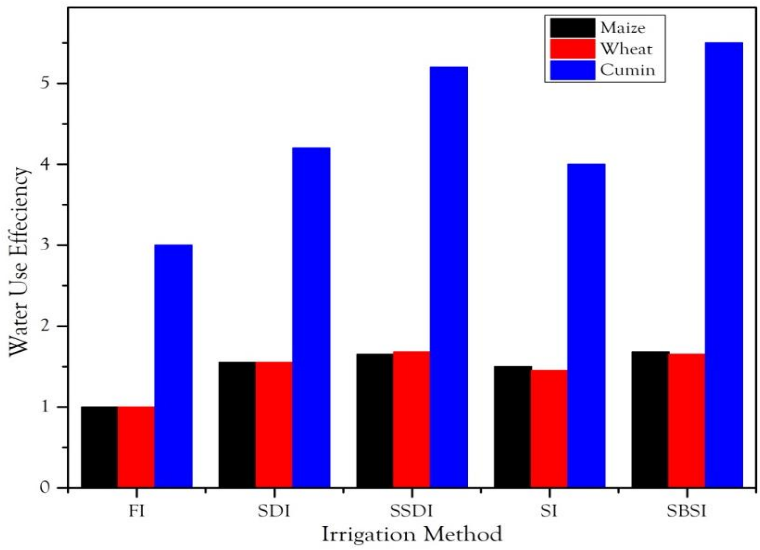

Figure 2. Water use efficiency (WUE) of maize, wheat, and cumin under five irrigation treatments. SBSI and SSDI achieved the highest WUE values across all crops, with cumin showing particularly efficient water usage under subsurface drip and sensor-based irrigation systems.

3.3 Irrigation Water Productivity (IWP)

IWP trends mirrored WUE patterns. SBSI achieved **up to 29% higher productivity** per unit of water used compared to FI. In maize, IWP values under SBSI reached **2.01 kg/m³**, while FI managed only

1.38 kg/m³. SDI and SI exhibited intermediate performances, with IWP ranging from **1.55–1.75 kg/m³**, depending on crop and irrigation volume applied.
This superior water productivity under smart irrigation systems demonstrates their potential to decouple yield growth from water consumption—a critical adaptation in water-scarce environments.

3.4 Soil Moisture Retention

The sensor measurements indicated that SBSI and SSDI treatments had a more constant soil moisture level over time, especially the root region (10 to 30 cm depth). The soil moisture in SSDI stayed at 18-22% volumetric water content (VWC) with less variation, where FI plots showed greater variation (11-25% VWC) and varied mostly by wet-dry transitions.As shown in **Table 2**, under SBSI and SSDI, moisture stability promoted less water stress period, which led to the efficient uptake of nutrients and uniform growth of roots, which leads to the high yield and WUE results.

Table 2:. Soil Moisture Retention Patterns (10–30 cm depth)

Irrigation Type	Moisture Range (VWC %)	Stability Description
FI	11–25%	Highly variable (wet–dry)
SSDI	18–22%	Stable moisture retention
SBSI	~18–22%	Stable with automated control

3.5 Economic Returns

Initial investment cost (e.g., sensors, controllers, subsurface tubing) were greater in SBSI and SSDI than in full irrigation but the operational cost per hectare was covered through less water and energy consumption, and greater crop revenue. The net returns of SBSI were 78,000 - 85,000 (Rs)/ha depending on crop whereas those of FI failed at 48,000 - 56,000 (Rs)/ha. Ratios of Benefit to Cost on SBSI and SSDI were established at 2.1-2.5 as opposed to 1.4-1.6 under conventional systems. Although SI was affordable to shallow-rooted crops such as wheat, it performed badly in deep-rooted crops because infiltration depth depended on low infiltration.

3.6 Integrated Discussions

This evidence leaves no doubt in the high level of performance and agronomic superiority of climate based irrigation systems (especially Smart-Based Surface Irrigation (SBSI) and Subsurface Drip Irrigation (SSDI)) in arid agro climatical regions. They do this by combining advantages of automation, site specific water management and accuracy delivery mechanism that result in optimum crop productivity, efficient use of water and fewer environmental degradation. On top of increasing yield, sources indicate that these systems contribute to conservation of resources, enhancement of soil health, and significant boost in the long-term net returns of farmers. The low water use efficiency (WUE) and irrigation water productivity (IWP) ability, which have considered a significant improvement through the application of SBSI and SSDI, is consistent with the existing evidence gathered by prior empirical studies on arid ecosystems in northwest India [3][4][5], arid agricultural lands in northwest China [7], and the sandy soil landmass in Egypt [13][14], where the same innovation in irrigation practices registered revolutionary outcomes. The retention of soil moisture and the ability of minimizing percolation losses that are conspicuous under these systems are direct solutions to the fundamental issues facing arid-zone agriculture especially in the case of sandy soils, which have low intrinsic water retention capacities. Although there is certain cost that has to be initially involved in implementing these technologies, the overall long term positive side which is greater productivity, usage of water, and sustainability is greatly evident as compared to the constraints. The operational utility of these irrigation systems in dryland areas is further strengthened by the positive environmental externalities of these systems in terms of decreased salinization, enhanced nutrient delivery and reduced waterlogging. Deploying an integrated policy and institutional response is required in scaling such Irrigation Innovations. Adoption barriers can be addressed through the government sponsorship of smallholder farmers by supporting the cost with targeted capital subsidies, provision of financing schemes and cost sharing methods. There also should be an emphasis on on-ground capacity building, agronomic advisory services and training on digital literacy with local contextualization to help unlock mainstreaming of smart irrigation practices. Conclusively, SBSI and the SSDI systems can be used to provide not only a technology-sustainable approach towards alleviating the water scarcity problem but also provide legible models of a climate-resistant and economically viable agriculture system in the cold and semi-arid regions.

4. CONCLUSION

This paper has critically evaluated the effectiveness of some of the climate smart irrigation methods i.e. drip irrigation, subsurface drip irrigation and deficit irrigation using sensors in arid agroecological areas. The analysis was carried out on the basis of water use efficiency (WUE), crop yield sensitivity and response to abiotic stressors (arid climate) in comparison with field data obtained in arid zones; in India (Rajasthan), Israel (Negev Desert) and other arid zones in North Africa. The results indicated that subsurface drip irrigation (SDI) ranked the best in terms of water utilization and it gave coherent moisture around the root zone which reduced evaporation losses. Optimal irrigation scheduling through sensor based deficit irrigation systems and irrigations with up to thirty to fifty percent water savings and adequate yield levels were possible when the systems are properly calibrated. The technologies therefore showed the capacity to significantly cut the water used per every unit of crop production, especially in belt climates that experience high evapotranspiration. Further, the combination of solar automation/renwable energy and real time system response to soil moisture enhanced the efficiency of smart irrigation methods since it eliminates human error and labor expenses. Nevertheless, glass houses require substantial investment in initial capital expenses, technical hurdles and long training of farmers who are unfamiliar with the technology are significant obstacles that make its scale-up in water-starved arid communities. In conclusion, climate-smart irrigation systems represent a sustainable pathway for improving agricultural productivity in arid zones. Their successful deployment will require localized field trials, capacity building programs, and policy support for infrastructure and financing. Future research should explore long-term socio-economic impacts, system resilience under climate extremes, and scalability across different crop types and soil conditions to enable wider adoption.

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