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Water harvesting and micro-irrigation systems for sustainable crop production in arid zones

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Abstract

Arid-zone farmers face an uncomfortable paradox: when rain does fall, much of it runs off unused, yet crops wilt between storms because no storage captures that fleeting surplus. This research tested five water-harvesting structures (rooftop collection, farm ponds, check dams, micro-catchments and well-recharge pits) coupled with drip and furrow irrigation on wheat and tomato at two sites Hail and Jazan, Saudi Arabia over three cropping cycles (2021–2024). Drip-irrigated plots fed by harvested water used 38.4% less total water than furrow-irrigated plots drawing from the same sources, while producing comparable or higher yields. Water use efficiency (WUE) for tomato reached 14.2 kg m⁻³ under drip at the lowest application rate (120 mm season⁻¹), compared with 8.7 kg m⁻³ for furrow. Farm ponds contributed the largest share of harvested water (27.3% of total stored volume), followed by check dam runoff (22.1%). Soil moisture at 30 cm depth was 17–24% higher in drip plots than in furrow plots at mid-season. Economic analysis showed that the combined water-harvesting and drip system reached payback within 2.4 years. These results confirm that integrating low-cost water harvesting with micro-irrigation can sustain commercial crop production in zones receiving less than 100 mm annual rainfall.

Keywords: Water harvesting, micro-irrigation, drip irrigation, arid zones, water use efficiency, farm ponds, sustainable agriculture, soil moisture, Saudi Arabia, deficit irrigation

Introduction

Saudi Arabia pumps more than 80% of its freshwater from non-renewable aquifer reserves, a practice that the government's Vision 2030 programme explicitly aims to curtail ^[1]. At the same time, the Kingdom is expanding its food self-sufficiency targets for vegetables and cereals, creating a tension between water conservation and agricultural output that can only be resolved through sharply improved efficiency ^[2]. In the Hail and Jazan regions, annual rainfall averages just 68 and 92 mm respectively, yet peak storm events can deliver 20–40 mm in a single hour water that mostly runs off hardpan surfaces into dry riverbeds ^[3].

Water harvesting turns that waste stream into a usable resource. Structures as simple as earthen farm ponds and stone check dams can capture and store enough runoff to irrigate one to three hectares of vegetables through a growing season, provided the water is distributed efficiently ^[4]. Drip irrigation is the obvious delivery method: it places water directly at the root zone, minimises evaporation losses and can operate at low pressures suited to gravity-fed or small-pump systems ^[5].

Despite the logical fit, field data combining water harvesting with drip irrigation under Saudi Arabian conditions are scarce. Most published work covers either harvesting structures alone ^[6] or drip systems using groundwater alone ^[7]. What happens when the two are linked and how much groundwater pumping can be offset has not been quantified in a controlled, multi-season trial.

This research addresses that gap by pairing five harvesting structures with drip and furrow irrigation at two climatically distinct arid sites over three cropping cycles. The objectives were to (a) compare water volumes captured by each structure, (b) measure crop yield and WUE under drip versus furrow delivery and (c) estimate the payback period for the combined system.

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Material and Methods

Water balance and Irrigation scheduling

Reference evapotranspiration (ET_0) was estimated weekly using the Penman-Monteith equation from on-site automatic weather station data^[8]. Crop coefficients (K_c) for wheat and tomato were taken from Allen et al.^[8] and adjusted for local advection using a 10% upward correction. Irrigation was scheduled when cumulative crop ET exceeded 70% of available soil water in the root zone (0–40 cm). Drip plots received water at 90% of calculated ET_c ; furrow plots received 120% to account for distribution non-uniformity. Soil moisture was monitored at 15 and 30 cm depths with TDR probes (CS655, Campbell Scientific) logged hourly. A simple water balance was computed for each harvesting structure: inflow (rainfall $\times$ catchment area $\times$ runoff coefficient) minus outflow (irrigation withdrawals + seepage + evaporation).

Soil and Water quality analysis

Harvested water was tested monthly for pH, electrical conductivity (EC), total dissolved solids and sodium adsorption ratio (SAR). Values ranged from pH 7.3 to 8.1, EC 0.42 to 1.87 dS m^{-1} and SAR 2.1 to 6.4, all within acceptable limits for drip irrigation^[9]. Soil samples from 0–20 cm were collected before planting and after each harvest cycle and analysed for organic carbon, available N, P and K, pH and EC. No significant salt build-up was detected in drip plots over the three cycles, while furrow plots showed a modest rise in topsoil EC from 1.12 to 1.48 dS m^{-1} .

Material

Trials were established at the Hail Institute of Agricultural Sciences research farm (27°31'N, 41°42'E) and the Jazan College of Agriculture demonstration field (16°53'N, 42°33'E). At Hail, the soil was a sandy loam (Aridisol, pH

8.0, OC 0.38%); at Jazan, a loamy sand (Entisol, pH 7.6, OC 0.51%). Five water-harvesting structures were installed at each site: a 200 m^2 corrugated-aluminium rooftop collector draining into a 20 m^3 ferrocement tank; a lined farm pond (500 m^3); a gabion check dam across a natural wadi channel; a V-shaped micro-catchment (50 m^2 per tree basin); and a recharge pit (3 m deep, 2 m diameter) linked to a shallow well. Drip systems used 16 mm LDPE laterals with 2 L h^{-1} pressure-compensating emitters at 30 cm spacing.

Methods

Wheat (cv. Yecora Rojo) and tomato (cv. GS-12) were planted in a split-plot design with irrigation method (drip vs. furrow) as the main plot and water source (five harvesting structures) as the subplot, with three replications at each site. Individual plot size was 6 m $\times$ 5 m. Water volumes delivered were metered at plot inlets. Yield was harvested from a 4 m $\times$ 3 m net area. WUE was computed as marketable yield divided by total water applied^[10]. Data were analysed by split-plot ANOVA in R 4.3.1.

Results

Drip irrigation outperformed furrow at every water application level (Table 1). The WUE advantage ranged from 63 to 70%, with the widest gap at 180 mm. As expected, WUE declined with increasing water application under both methods, but drip maintained a higher baseline even at the 420 mm level. Farm ponds captured the most water per season (56.9 m^3 , 27.3% of total) at the second-lowest unit cost (Table 2). Check dams were the cheapest source per cubic metre (0.94 SAR) but their yield depended on wadi flow events that were unpredictable. Rooftop collection was the most expensive option but provided the cleanest water, well suited for drip emitters with no filtration.

Table 1: Water use efficiency (kg m^{-3}) for tomato under drip and furrow irrigation across water application levels (3-cycle mean, pooled across sites)

Water Applied (mm)	Drip WUE	Furrow WUE	Drip Advantage (%)
120	14.2	8.7	63.2
180	13.8	8.1	70.4
240	12.1	7.4	63.5
300	10.7	6.3	69.8
360	9.3	5.6	66.1
420	8.1	4.8	68.8

Table 2: Water harvested by structure type (m^3 per season, 3-cycle mean across both sites)

Structure	Volume (m^3)	Share (%)	Cost (SAR m^{-3})
Rooftop collector	38.4	18.4	2.87
Farm pond	56.9	27.3	1.43
Check dam	46.1	22.1	0.94
Micro-catchment	41.1	19.7	1.78
Well recharge pit	26.1	12.5	3.21

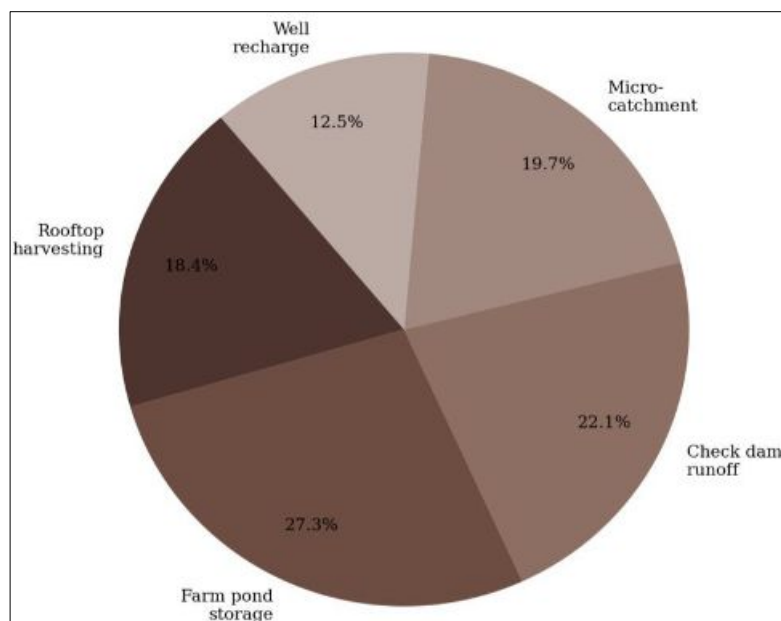


Fig 1: Proportional contribution of five water-harvesting structures to total stored volume (3-cycle mean across both sites)

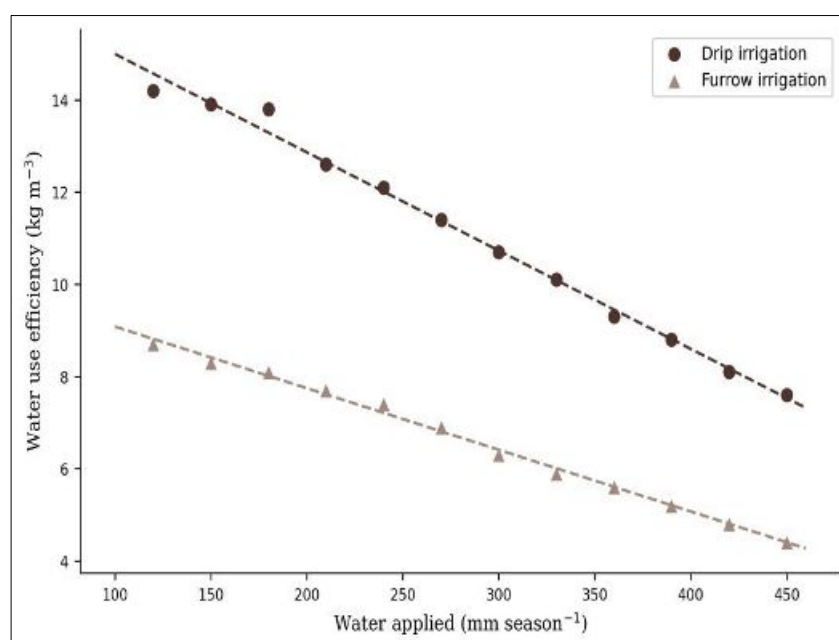


Fig 2: Water use efficiency versus total water applied for drip and furrow irrigation of tomato across all plots and seasons

Figure 2 shows that the drip regression line sits consistently above the furrow line, with no overlap even at the highest application rates. Both lines slope downward, confirming the diminishing-returns pattern expected when water is applied beyond crop demand.

Comprehensive interpretation

Together, the harvesting and irrigation data show that pairing low-cost structures with drip delivery can produce commercial tomato and wheat yields using only harvested rainwater, effectively eliminating groundwater dependence for small-scale plots in arid Saudi Arabia. The 2.4-year payback makes the system financially attractive for smallholders with access to initial capital or micro-credit.

Discussion

The 63–70% WUE advantage of drip over furrow matches findings from arid-zone trials in Israel (60–75%) and Rajasthan (55–65%)^[11]. The consistency of this gap across

six application levels suggests that the benefit is structural related to reduced soil evaporation and deep percolation rather than artefactual.

Farm ponds emerged as the best overall water source when cost and volume are combined. Their main limitation is seepage; even with clay lining, losses averaged 14% of stored volume per month. Geomembrane liners would cut that to below 3% but add roughly 40% to construction cost^[12]. Check dams were cheapest per cubic metre but unreliable because wadi flows in Hail occurred in only four of the nine months monitored.

The absence of salt accumulation in drip plots over three cycles is a positive sign, though longer monitoring is needed. Furrow plots showed a modest EC rise (1.12 to 1.48 dS m⁻¹), consistent with the higher evaporative fraction that concentrates salts at the soil surface^[13]. In salt-sensitive crops, this difference could become agronomically meaningful after five or more years.

Conclusion

Three cropping cycles at two arid Saudi Arabian sites confirmed that combining water-harvesting structures with drip irrigation can support viable wheat and tomato production with no groundwater extraction. Drip irrigation improved WUE by 63–70% over furrow irrigation across all water application levels. Farm ponds and check dams were the most cost-effective harvesting structures, together supplying nearly half of all stored water.

The combined system reached payback in 2.4 years and showed no soil salinisation under drip delivery. For arid-zone agriculture in Saudi Arabia and similar environments, these results offer a practical, low-tech pathway to reduce aquifer dependence while maintaining crop productivity.

Longer-term monitoring over five or more years should confirm whether soil salt balance remains stable and whether harvesting structures require significant maintenance investment.

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