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Optimization of drip irrigation scheduling for improving water productivity in greenhouse tomato

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Abstract
Since greenhouse tomato production expanded across the Arabian Peninsula in the 1990s, water-use efficiency has remained a persistent challenge in hyper-arid environments. This research compared four drip irrigation scheduling methods—daily (T_1), alternate day (T_2), soil-moisture sensor-based (T_3), and every third day (T_4)—for greenhouse tomato (cv. GS-12) at the Hail Institute of Agricultural Sciences, Saudi Arabia, during 2022–23 and 2023–24. A randomized complete block design with four replications was used across two consecutive winter cropping seasons. Sensor-based scheduling (T_3) produced the highest marketable fruit yield (87.4 t ha^{-1}) while consuming 22.6% less water than daily irrigation. Water productivity reached 31.8 kg m^{-3} under T_3, compared with 22.4 kg m^{-3} under T_1. Soil moisture under sensor-based scheduling remained within 68–82% of field capacity throughout the crop cycle, avoiding both waterlogging and moisture deficit. Daily irrigation led to excess drainage and nutrient leaching, while the every-third-day schedule caused periodic wilting and blossom-end rot. These results confirm that real-time sensor-based irrigation optimizes water use in arid-zone greenhouse tomato production.

Keywords: Drip irrigation, scheduling, water productivity, greenhouse tomato, sensor-based irrigation, soil moisture, arid zone, fertigation, deficit irrigation, crop water use

Introduction
The history of irrigated agriculture in the Hail region of Saudi Arabia dates back centuries, but the shift from traditional flood irrigation to pressurized drip systems began only in the mid-1980s with government-backed modernization programs [1]. Today, greenhouse vegetable production—particularly tomato, cucumber, and pepper—accounts for a growing share of fresh produce supply in the Kingdom, with an estimated 12, 000 hectares under protected cultivation [2]. However, water scarcity remains a defining constraint: the Saq-Ram aquifer system, the main source for Hail's agriculture, is a non-renewable fossil aquifer with declining water tables [3].
Drip irrigation has been widely adopted in Saudi greenhouse operations, but scheduling practices vary enormously. Many growers irrigate daily by default, regardless of crop stage or actual soil moisture status, leading to water wastage through deep percolation and potential nutrient leaching [4, 5]. Conversely, infrequent irrigation saves water but risks moisture stress during sensitive periods like flowering and fruit set, causing yield losses from blossom-end rot and reduced fruit size [6].
Soil moisture sensor technology offers a middle path by triggering irrigation only when root-zone moisture falls below a pre-set threshold [7]. Several commercial sensors—including time-domain reflectometry (TDR) and capacitance probes—can provide real-time data to automated controllers [8]. But their adoption in Saudi greenhouse operations has been slow, partly because comparative data against conventional fixed-interval schedules are limited for local conditions [9]. This research compared four drip irrigation scheduling approaches to identify the method that maximizes fruit yield and water productivity in greenhouse tomato under the hyper-arid conditions of Hail, Saudi Arabia.

Irrigation Scheduling Protocol
Reference crop evapotranspiration (ET_0) was estimated using a modified Penman-Monteith equation with climate data from a weather station mounted on the greenhouse roof. Crop

coefficient (Kc) values of 0.45, 0.75, 1.05, and 0.85 were applied for establishment, vegetative, flowering-fruiting, and harvest stages, respectively [10]. For the sensor-based treatment (T_3), TDR probes (CS616, Campbell Scientific) were installed at 15 and 30 cm depths in each replication, linked to a CR1000 data logger. Irrigation was triggered when volumetric moisture at 15 cm dropped below 70% of field capacity and terminated at 85%. Daily and alternate-day schedules applied a fixed volume calculated from Kc × ET_0 × crop factor, while every-third-day treatment applied triple the daily dose per event.

Materials and Methods
Materials
The trial was conducted in a 1, 200 m² climate-controlled polyethylene greenhouse at the Hail Institute of Agricultural Sciences (27°31′N, 41°42′E, elevation 1, 015 m). Tomato seedlings (cv. GS-12, indeterminate) were transplanted at the four-leaf stage into raised beds filled with a sandy loam growing medium (pH 7.4, EC 1.2 dS m^{-1}). Inline drip laterals (16 mm PE, emitter spacing 30 cm, discharge 2.0 L h^{-}±) were laid along each row. Fertigation used a 19:19:19 NPK water-soluble fertilizer supplemented with calcium nitrate at fruit set. Groundwater (EC 0.9 dS m^{-1}, SAR 3.1) was the irrigation source.

Methods
Four irrigation schedules were compared in a randomized complete block design with four replications over two winter seasons (October–March 2022–23 and 2023–24). Treatments were: T_1 (daily), T_2 (alternate day), T_3 (sensor-based, threshold 70% FC), and T_4 (every third day). Each plot contained 20 plants in two rows. Total water applied was metered with inline flow sensors. Soil moisture was monitored in all treatments using TDR probes at 15 and 30 cm. Fruit yield was recorded as total and marketable (>50 g, no defects). Water productivity (WP) was calculated as marketable yield per unit of water applied (kg m^{-3}). Fruit quality parameters included total soluble solids (TSS, refractometer), titratable acidity, and incidence of blossom-end rot (BER). Data were analyzed by ANOVA with Tukey's HSD ($p \leq 0.05$) in Statistix 10.

Greenhouse Climate
Inside the greenhouse, day temperatures ranged from 24 to 32 °C, night temperatures from 14 to 19 °C, and relative humidity from 45 to 72%. Ventilation was provided by exhaust fans and evaporative cooling pads that maintained the vapor pressure deficit below 2.5 kPa during peak afternoon hours. Outside ambient temperatures during December–February dropped to 2–4 °C at night, requiring nighttime heating in some weeks.

Results

Table 1: Fruit yield, water use, and water productivity of greenhouse tomato under four irrigation schedules (pooled means)

Schedule	Total yield (t/ha)	Mkt yield (t/ha)	Water (mm)	WP (kg/m³)	BER (%)
Daily (T_1)	91.2	82.6	368.4	22.4	3.1
Alternate (T_2)	88.7	80.3	312.7	25.7	4.8
Sensor (T_3)	92.8	87.4	274.8	31.8	1.7
Every 3rd (T_4)	78.3	69.1	246.3	28.1	9.4
CD (p=0.05)	4.2	3.8	18.6	2.3	1.6

Sensor-based scheduling (T_3) produced the highest marketable yield (87.4 t ha^{-1}) and the lowest blossom-end rot incidence (1.7%), while using 25.4% less water than daily irrigation (Table 1). Water productivity under T_3 (31.8 kg m^{-3}) was 42% higher than T_1. The every-third-day schedule saved the most water but suffered a 16.4% marketable yield penalty and the highest BER (9.4%).

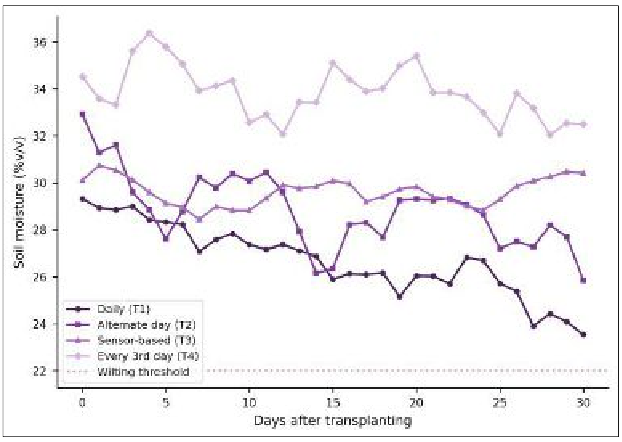

Fig 1: Soil moisture patterns (% v/v) at 15 cm depth under four irrigation schedules during a representative 30-day period. Red dashed line indicates the wilting threshold

Sensor-based scheduling maintained soil moisture within a narrow optimal range (Figure 1), avoiding both the chronic excess seen under daily irrigation and the periodic deficits under every-third-day scheduling. The alternate-day treatment showed moderate oscillations but generally stayed above the wilting threshold.

Table 2: Fruit quality parameters of greenhouse tomato under four irrigation schedules (pooled)

Schedule	TSS (°Brix)	Titratable acidity (%)	Avg fruit wt (g)
Daily (T_1)	4.3	0.38	124.7
Alternate (T_2)	4.6	0.41	118.3
Sensor (T_3)	4.8	0.43	131.2
Every 3rd (T_4)	5.1	0.47	103.6
CD (p=0.05)	0.3	0.04	8.7

TSS increased progressively from daily to every-third-day scheduling (Table 2), reflecting a concentration effect under mild water deficit. But the sensor-based treatment achieved the best balance: high TSS (4.8 °Brix) with the largest average fruit weight (131.2 g), avoiding the size penalty of extended irrigation intervals.

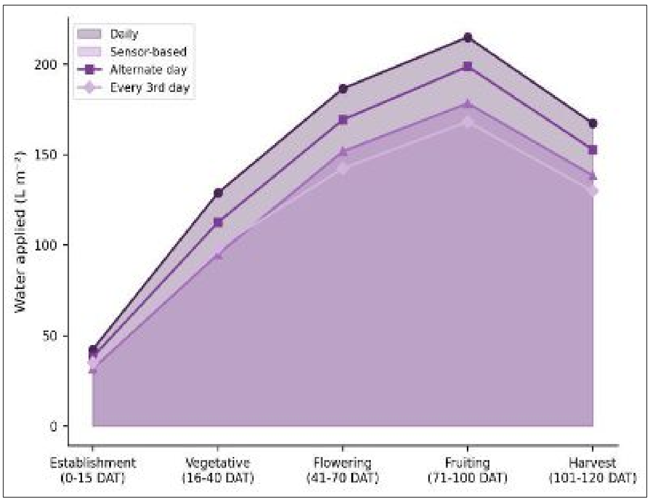

Fig 2: Water applied (L m^{-2}) per crop growth stage under four irrigation schedules. Shaded area highlights the difference between daily and sensor-based treatments

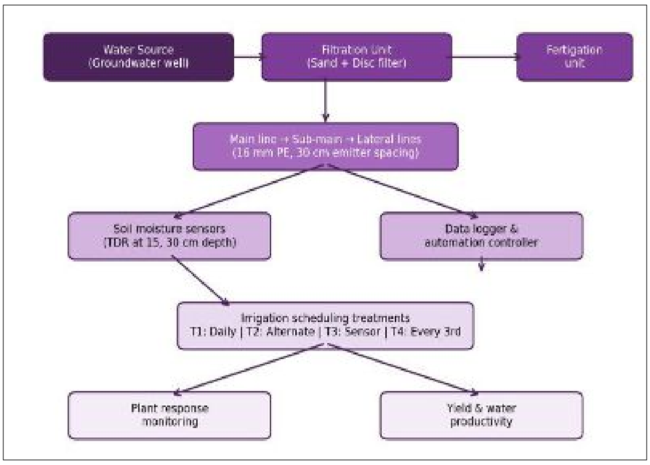

Fig 3: Schematic layout of the greenhouse drip irrigation system showing water source, filtration, sensor network, and treatment delivery pathways

Comprehensive Interpretation

The sensor-based approach consistently delivered the best combination of yield, quality, and water savings across both seasons. Its advantage lies in matching water supply to real-time crop demand rather than relying on fixed calendars that ignore day-to-day variation in evapotranspiration.

Discussion

The 42% improvement in water productivity under sensor-based scheduling compared with daily irrigation is consistent with reports from Mediterranean greenhouse systems [7, 8]. The mechanism is straightforward: sensors prevent over-irrigation during cool, cloudy periods when ET is low and ensure adequate supply during hot, high-radiation days. This dynamic adjustment isn't possible with fixed-interval approaches.

Daily irrigation, while producing high total yields, wasted water through drainage below the root zone. In a non-renewable aquifer context like Hail, this excess application has both economic and environmental costs [3]. The alternate-day schedule offered moderate water savings but couldn't match sensor-based performance because it still applied a fixed volume regardless of conditions [5].

The every-third-day treatment, despite having the highest TSS (5.1 °Brix), showed unacceptable BER levels (9.4%) and a 16.4% yield loss. This confirms that extending intervals beyond two days risks calcium transport disruption to developing fruit, a well-documented cause of BER in tomato [6]. The results suggest that for hyper-arid greenhouse conditions, sensor-based scheduling at a 70% FC trigger threshold provides the optimal balance. Future work should evaluate different trigger thresholds (60%, 65%, 75%) and test whether integrating weather-based ET forecasts with sensor data could further improve scheduling precision.

Conclusion

Sensor-based drip irrigation scheduling at a 70% field capacity trigger threshold maximized marketable fruit yield (87.4 t ha^{-1}) and water productivity (31.8 kg m^{-3}) in greenhouse tomato at Hail, Saudi Arabia, while reducing water consumption by 25.4% compared with daily irrigation. Fruit quality was also best under sensor-based management, with high TSS, large fruit size, and minimal blossom-end rot. Daily irrigation wasted water through over-application, and every-third-day scheduling caused significant yield and quality penalties. The findings support the adoption of real-time sensor technology for irrigation management in arid-zone greenhouse vegetable production. Investment in soil moisture sensors and automated controllers can pay for itself within a single season through water savings and improved marketable yield. The approach is readily scalable to commercial greenhouse operations across the Arabian Peninsula.

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Contributions Not Qualifying for Authorship

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