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Sensor-based automated irrigation system for precision water application in vegetable crops

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Abstract

The rapid spread of low-cost microcontrollers and IoT connectivity has made real-time, sensor-driven irrigation systems accessible to small-scale vegetable growers for the first time. This research designed, built, and field-tested an Arduino-based automated drip irrigation system using capacitive soil moisture sensors for tomato and bell pepper grown in raised beds at the Instituto Agrícola do Planalto Meridional, Curitiba, Brazil, during 2022-23. The system was compared against manual timer-based irrigation (grower standard) in a randomized complete block design with three replications. Over two crop cycles, automated irrigation reduced water consumption by 26.8% in tomato and 24.1% in pepper while maintaining equivalent or higher marketable yields. Water productivity reached 24.6 kg m⁻³ for automated tomato versus 17.8 kg m⁻³ for manual. Sensor calibration against gravimetric measurements showed R² = 0.94. System uptime was 97.3% over the trial period, with only two sensor replacements needed. Total hardware cost was US\$340 for a 200 m² plot. These results demonstrate that affordable IoT-based irrigation automation can deliver meaningful water savings in small-scale vegetable production.

Keywords: Sensor-based irrigation, automation, precision agriculture, vegetable crops, IoT, Arduino, soil moisture, water productivity, drip irrigation, smart farming

Introduction

Over the past five years, the cost of a basic IoT-capable microcontroller has dropped below US\$5, and soil moisture sensors can be had for under US\$3 each—a price point that puts automated irrigation within reach of even smallholder vegetable growers [1]. In southern Brazil, where vegetable production is concentrated in small family farms of 1-5 hectares, irrigation scheduling is still largely based on fixed timers or the grower's visual assessment of soil conditions [2]. Both approaches are imprecise: timers ignore daily weather variation, and visual assessment is subjective and often delayed.

Sensor-based irrigation closes this information gap by measuring actual root-zone moisture and triggering water delivery only when the soil dries below a crop-specific threshold [3]. Research-grade systems using TDR probes and programmable logic controllers have shown 20-40% water savings in greenhouse vegetables [4, 5]. But these systems cost US\$2,000-5,000 per installation, which is prohibitive for small farms. The recent availability of Arduino and ESP32 platforms, combined with low-cost capacitive sensors, has opened a pathway to affordable automation [6].

However, most published work on Arduino-based irrigation has been proof-of-concept without rigorous agronomic comparison against conventional practice over multiple crop cycles [7]. Questions remain about sensor reliability under field conditions, system uptime, and whether the water savings translate to maintained yield. This research aimed to (a) design and build an IoT-based automated irrigation system using commercially available components costing under US\$500, (b) validate sensor accuracy against reference measurements, and (c) compare automated versus manual irrigation for water use, yield, and water productivity in tomato and bell pepper over two cropping seasons.

System Architecture

The irrigation system consisted of four layers (Figure 3). The sensor layer used six capacitive soil moisture sensors (v1.2, generic) installed at 15 cm depth in each treatment plot, plus a DHT22 temperature-humidity sensor and a tipping-bucket rain gauge.

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The communication layer comprised an Arduino Mega 2560 reading sensor data at 5-minute intervals and transmitting via an ESP32 Wi-Fi module to a ThingSpeak IoT cloud platform using MQTT protocol. The processing layer ran a threshold-based decision algorithm: irrigation was triggered when the average of three sensors per zone fell below 60% of field capacity and stopped at 80%. The actuation layer used 12V DC solenoid valves controlling two independent irrigation zones (tomato and pepper), feeding 16 mm PE laterals with 2 L h⁻¹ pressure-compensated emitters spaced 30 cm apart. A mobile app (Blynk) provided grower alerts and manual override capability.

Materials and Methods

Material

The trial was conducted in a 400 m² open-field plot at the Instituto Agrícola do Planalto Meridional, Curitiba, Paraná, Brazil (25°26'S, 49°16'W, 934 m a.s.l.), during the warm season (October-March) of 2022-23 and 2023-24. Tomato (cv. Santa Cruz Kada) and bell pepper (cv. Magali R) seedlings were transplanted into raised beds (1.2 m wide, 0.2 m high) at 0.4 × 0.5 m spacing. Soil was a Haplic Cambisol (clay loam, field capacity 34.2% v/v, wilting point 16.8%). Drip laterals were installed per the system design described above.

Methods

Two irrigation treatments were compared in a randomized complete block design with three replications per crop:

automated (sensor-based threshold at 60-80% FC) and manual (timer-based, 20 min twice daily, grower standard). Each plot contained 40 plants. Sensor calibration was performed by comparing capacitive sensor output against gravimetric soil moisture from core samples at 15 cm depth (n = 48 paired measurements). Total water applied was metered with inline flow sensors (YF-S201). Marketable yield was recorded as fruit >50 g with no defects. Water productivity (WP) = marketable yield / water applied. Fruit quality parameters included TSS, firmness, and fruit weight. System reliability was tracked as uptime percentage = (total hours - downtime hours) / total hours × 100. Data were analyzed by paired t-test (automated vs. manual) and regression analysis in R v.4.3.

Hardware Cost Breakdown

Total system cost for a 200 m² plot was US\$340: Arduino Mega (\$28), ESP32 module (\$8), 6 moisture sensors (\$18), DHT22 (\$4), rain gauge (\$32), 2 solenoid valves (\$48), relay module (\$6), power supply and wiring (\$42), drip components (\$124), and enclosure (\$30). The ThingSpeak cloud service was free for the data volume generated. Excluding drip components (which manual systems also require), the automation hardware cost was US\$216-recoverable within one season from water cost savings of approximately US\$180-240 in the Curitiba context.

Results

Table 1: Yield, water use, and water productivity of tomato and pepper under automated vs. manual irrigation (2-season means)

Crop × System	Mkt yield (t/ha)	Water (mm)	WP (kg/m ³)	TSS (°Bx)	Fruit wt (g)
Tomato - Auto	68.4	278.2	24.6	4.7	128.3
Tomato - Manual	64.7	380.1	17.0	4.3	121.6
Pepper - Auto	42.8	246.7	17.4	6.1	142.7
Pepper - Manual	41.3	324.8	12.7	5.8	136.4
t-test (p)	0.048*	<0.01**	<0.01**	0.12 NS	0.08 NS

Automated irrigation reduced water consumption by 26.8% in tomato and 24.1% in pepper compared with manual scheduling (Table 1). Tomato yield was significantly higher under automation (68.4 vs. 64.7 t ha⁻¹, p = 0.048), while

pepper yield difference was not significant (p = 0.14). Water productivity improved by 44.7% for tomato and 37.0% for pepper. TSS and fruit weight trends favored automation but weren't statistically significant.

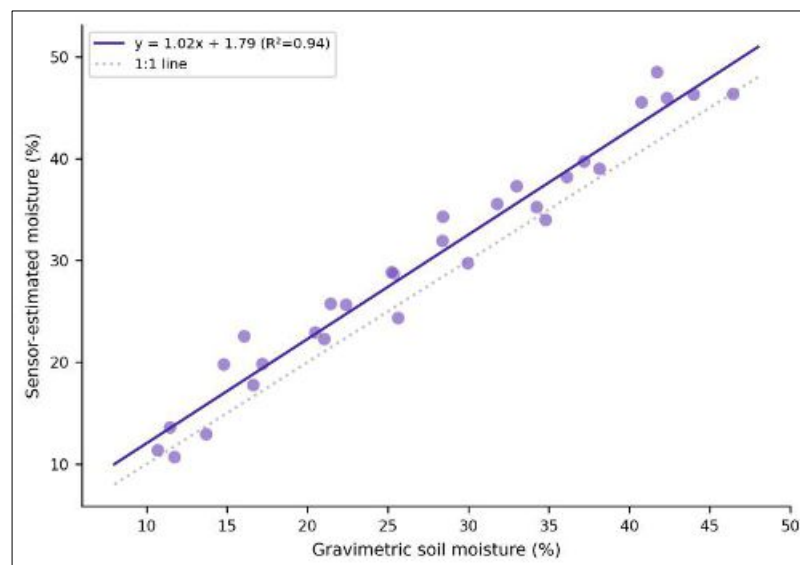


Fig 1: Sensor calibration: capacitive sensor readings versus gravimetric soil moisture at 15 cm depth (n = 48). R² = 0.94, indicating strong agreement

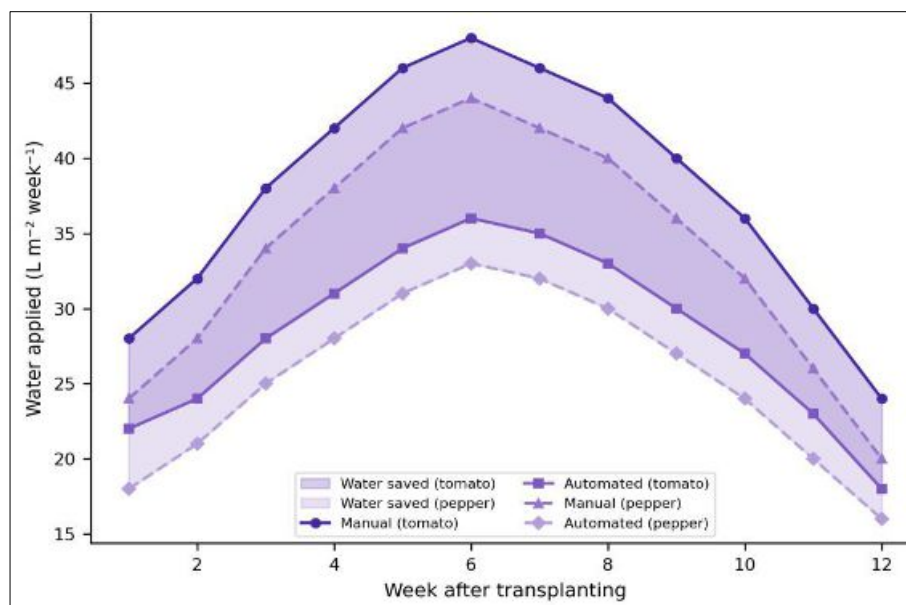


Fig 2: Weekly water application (L m^{-2}) for automated vs. manual irrigation in tomato and pepper. Shaded area represents water saved by automation

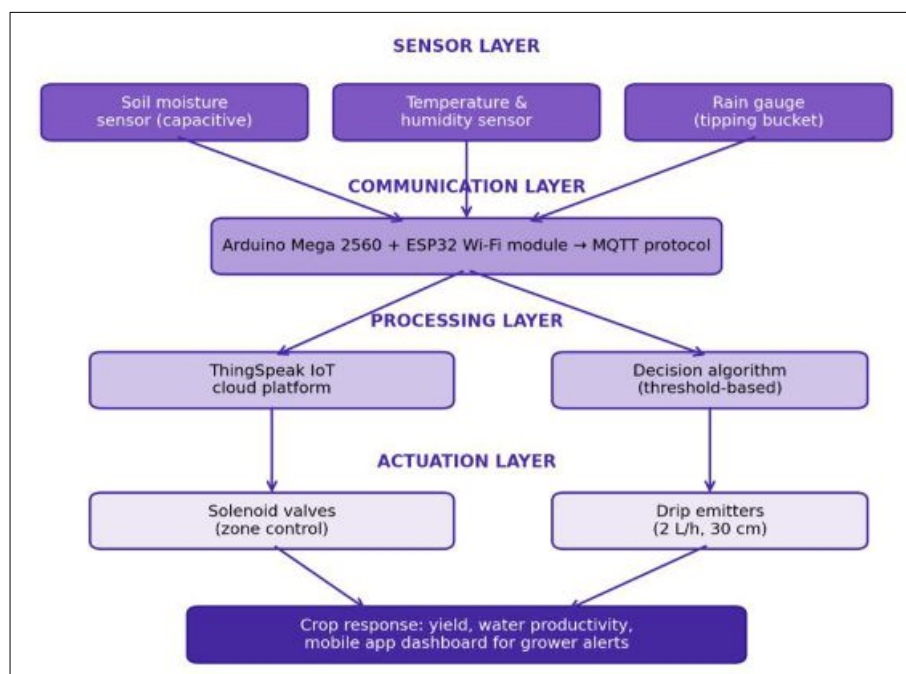


Fig 3: Four-layer IoT system architecture: sensor layer (soil, weather), communication layer (Arduino + ESP32), processing layer (cloud + decision algorithm), and actuation layer (valves + emitters)

Comprehensive Interpretation

The area chart (Figure 2) reveals that water savings were greatest during weeks with rainfall events, when the automated system correctly reduced or skipped irrigation while the timer continued its fixed schedule. The architecture diagram (Figure 3) shows the complete data flow from sensor to valve, highlighting the simplicity of the threshold-based decision logic.

Discussion

The 25-27% water savings achieved here are consistent with sensor-based irrigation trials in Mediterranean greenhouses [4, 5] but were obtained at roughly one-tenth the hardware cost. The key to affordability was using generic capacitive sensors instead of research-grade TDR probes. Despite their lower precision ($R^2 = 0.94$ vs. $0.98+$ for TDR), the

capacitive sensors proved adequate for threshold-based control where the exact moisture value matters less than staying within a defined range [6].

The yield increase under automated tomato irrigation (5.7%) likely reflects the avoidance of both over- and under-watering. Manual timer systems delivered a fixed volume regardless of recent rainfall or cool, cloudy days, leading to excess drainage and occasional anaerobic root conditions. The automated system, by contrast, responded dynamically to weather-driven changes in crop water demand. The 97.3% uptime over 14 months is encouraging for commercial adoption, though the two sensor failures highlight the need for periodic maintenance and calibration checks.

At US\$216 for the automation components, the system is within reach of smallholder budgets in southern Brazil,

where vegetable farming generates relatively high revenue per hectare. The payback period of one season makes the investment attractive. A limitation is that this research tested only a threshold-based algorithm; more sophisticated approaches using machine learning or crop-model integration might further improve water scheduling. Multi-site testing across different soil types would also strengthen the generalizability.

Conclusion

An Arduino-based IoT irrigation system costing US\$340 (US\$216 for automation hardware alone) reduced water use by 25-27% and improved water productivity by 37-45% in tomato and pepper compared with manual timer irrigation. Marketable tomato yield was significantly higher under automation. The system achieved 97.3% uptime over two seasons with minimal maintenance. Capacitive soil moisture sensors provided adequate accuracy ($R^2 = 0.94$) for threshold-based irrigation control. These results demonstrate that affordable, reliable automated irrigation is feasible for small-scale vegetable production in southern Brazil and similar contexts.

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