
DESIGN AND PROOF-OF-CONCEPT EVALUATION OF A GROWTH-STAGE-ORIENTED ESP32-BASED SMART DRIP IRRIGATION SYSTEM FOR BELL PEPPER PRODUCTION IN SEMI- ARID NIGERIA

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ABSTRACT

Water availability and changing crop water demand make irrigation management difficult in semi-arid production systems. This paper presents the design and proof-of-concept evaluation of a growth-stage-oriented smart drip irrigation prototype for bell pepper. The system uses an ESP32 controller with a capacitive soil-moisture sensor, DHT22 temperature and humidity sensor, DS18B20 soil-temperature sensor, YF-S201 flow sensor, DS3231 real-time clock, relay-controlled pump, drip line, LCD, and manual controls. We defined a growth-stage framework using days after transplanting (DAT), provisional soil-moisture thresholds, and maximum irrigation durations; these settings are engineering assumptions rather than validated agronomic optima. We established five four-week-old bell pepper seedlings in one prototype box and monitored them over 19 morning/evening observation periods. The recorded dataset contained air temperature, soil temperature, relative humidity, soil moisture, and independently measured irrigation volume. Across the 19 periods, total recorded irrigation was 6.35 L, comprising 2.65 L in the morning and 3.70 L in the evening. Mean air temperature was 24.48 °C in the morning and 32.37 °C in the evening, while mean soil moisture was 86.79% and 65.26%, respectively. Three response-time observations of 0.488, 0.406, and 0.590 s gave a mean of 0.495 ± 0.092 s. The observations demonstrate that the prototype can acquire environmental data and deliver measured irrigation under live-crop conditions, but they do not establish seasonal water-use efficiency or water-saving performance. Further replicated calibration, controlled comparison, full-cycle crop monitoring, and field testing are required.

Keywords: smart irrigation; drip irrigation; ESP32; bell pepper; growth-stage irrigation; water management

1. INTRODUCTION

1.1 Background of the Study

Agricultural production in semi-arid environments is constrained by water availability, rainfall variability, and irrigation management. Bell pepper (*Capsicum annum*) is a high-value crop whose water requirement changes with development. The FAO-56 framework recognizes the influence of crop stage and environmental conditions on crop water requirements (Allen et al., 1998). Applying one irrigation rule throughout the crop cycle may therefore be less responsive than a strategy that considers crop development together with measured soil and environmental conditions.

Recent smart-agriculture research shows that low-cost microcontrollers and connected sensing can be used to automate irrigation and monitor environmental conditions. Pereira et al. (2023), for example, demonstrated an ESP32-based smart drip irrigation system, while Pereira et al. (2023) describe the broader use of IoT technologies for agricultural monitoring and automation. More advanced systems have also combined environmental data with artificial intelligence or predictive methods to support irrigation decisions (Gaitan et al., 2025; Preite & Vignali, 2024).

However, the usefulness of a smart irrigation system depends not only on the availability of sensors but also on how the control strategy is related to crop development and local conditions. Wanyama et al. (2024) identified affordability, infrastructure, water scarcity, and contextual suitability as important considerations for smart irrigation in sub-Saharan Africa. A practical system for this context therefore needs to combine relatively simple hardware with a control framework that can be refined from local observations.

1.2 Research Gap

Many low-cost irrigation controllers use a fixed soil-moisture threshold or fixed schedule. Such approaches automate water delivery but do not explicitly provide a mechanism for changing irrigation targets with crop development. This study combines environmental sensing and drip irrigation with a growth-stage-oriented control framework. The contribution is the prototype architecture, stage-based control concept, and live-crop observations, not a claim of validated seasonal water saving.

1.3 Sustainable Development Goal Relevance

The work aligns with SDG 2 through sustainable crop production; SDG 6 through agricultural water management; SDG 9 through embedded sensing and automation; SDG 12 through responsible resource use; SDG 13 through adaptation to water scarcity and variable conditions; and SDG 15 through sustainable soil and water management. These are project alignments, not measured SDG outcomes (United Nations, 2015).

1.4 Aim and Objectives

The aim was to design and evaluate, at proof-of-concept scale, a growth-stage-oriented ESP32-based smart drip irrigation system for bell pepper under semi-arid conditions. The objectives were to assemble the prototype; define a provisional DAT-based irrigation framework; integrate environmental sensing, timekeeping, flow measurement, and pump control; and characterize measured environmental conditions, irrigation volumes, and sensor response.

2. MATERIALS AND METHODS

2.1 System Components and Architecture

The prototype was centred on an ESP32 development board. A capacitive sensor measured soil moisture; a DHT22 measured air temperature and relative humidity; a DS18B20 measured soil temperature; and a YF-S201 monitored water flow. A DS3231 provided time information, while a relay, pump, and drip line delivered water. An I²C LCD displayed measurements, and push buttons provided local control.

The current implementation used local sensing, timekeeping, pump actuation, and manual interaction. The ESP32 provides a platform for later network connectivity, but network/cloud performance was not measured.

2.2 Firmware and Irrigation Control

The firmware acquires sensor measurements every two seconds and averages ten analogue soil-moisture readings before converting them to percentage values using programmed dry and wet endpoints. It reads the DHT22, DS18B20, YF-S201, and DS3231, and refreshes the LCD at about 0.5-second intervals. Automatic irrigation uses two fixed five-minute daily windows with manual override. The growth-stage framework was not the control routine used for the reported irrigation records.

The implemented automatic pump control uses two fixed five-minute daily windows, together with a manual pump override. The growth-stage-oriented algorithm described in this paper is therefore a control framework developed around the prototype rather than a fully validated adaptive control routine operating in the reported dataset. This distinction is important because the measured irrigation records cannot be attributed experimentally to the proposed stage-specific thresholds.

2.3 Growth-Stage-Oriented Control Framework

The framework uses days after transplanting (DAT) to associate crop development with a provisional moisture threshold and maximum irrigation duration. FAO-56 provides the conceptual basis for stage-dependent crop water requirements (Allen et al., 1998), but it does not prescribe the exact sensor percentages used here. The settings in Table 1 are engineering assumptions requiring crop-based calibration.

Table 1: Provisional growth-stage ranges and control settings.

Growth stage	Provisional DAT range and basis	Moisture threshold	Maximum duration
Early establishment	0–14 DAT; root establishment after transplanting	$\geq 60\%$	3 min/cycle
Vegetative	15–35 DAT; canopy and vegetative growth	$\geq 50\%$	5 min/cycle
Flowering	36–55 DAT; flowering and early reproductive development	$\geq 55\%$	8 min/cycle
Fruiting	56–85 DAT; fruit set and fruit expansion	$\geq 55\%$	8 min/cycle
Maturity	86 DAT and beyond; ripening and harvest development	$\geq 45\%$	4 min/cycle

The DAT ranges in Table 1 make the framework explicit but are not measured phenological boundaries. Flowering and fruiting share the same provisional threshold and duration because both are treated as water-sensitive reproductive stages; this is a design choice, not evidence that their water requirements are identical.

2.4 Calibration and Measurement Verification

The soil-moisture conversion uses programmed dry and wet reference endpoints of 2500 and 1135 ADC units. The available records do not contain replicated reference-instrument comparisons for the moisture, temperature or humidity sensors; therefore, percentage accuracy and calibration error are not reported. Irrigation volume was measured with a calibrated cylinder. Three response-time readings were retained, allowing mean, standard deviation and range to be reported.

Irrigation volume was measured independently with a calibrated measuring cylinder. The response-time test retained three signal-detection readings, allowing the mean and sample standard deviation to be calculated. The response-time measurement represents sensor signal detection and should not be interpreted as total environmental-change-to-pump-actuation latency.

2.5 Crop Establishment and Observation Procedure

Five healthy bell pepper seedlings, approximately four weeks old at transplanting, were established in one prototype box. The plants shared one soil environment and irrigation system and therefore represent one experimental unit rather than five independent replicates. Morning and evening readings were collected for 19 observation periods. No separate control or formal randomization was used, so the study does not support inferential comparison with another irrigation treatment.

No separate control treatment was used, and no formal randomization was performed because the work involved one prototype unit and was intended to characterize system operation under live-crop conditions. These design limitations prevent inferential comparison with a fixed-threshold or conventional irrigation treatment.

2.6 Data Analysis

Means, ranges and sample standard deviations were calculated for the 19 morning/evening observations. Total irrigation was obtained by summing recorded volumes, and the three response-time readings were summarized by mean, sample standard deviation and range. No seasonal saving

percentage or inferential treatment test was calculated because there was no completed crop cycle or replicated control.

3. RESULTS

3.1 Environmental and Irrigation Observations

The complete observation record is presented in Table 2. The data show clear differences between morning and evening conditions. Mean air temperature increased from 24.48 °C in the morning to 32.37 °C in the evening, while mean soil temperature increased from 24.59 °C to 32.74 °C. Mean relative humidity decreased from 85.37% to 63.95%, and mean soil moisture decreased from 86.79% to 65.26%.

Table 2: Complete morning and evening observation record (n = 19 observation periods).

Obs.	Air temp. AM/PM (°C)	Soil temp. AM/PM (°C)	RH AM/PM (%)	Moisture AM/PM (%)	Water AM/PM (mL)
1	31.5 / 37.0	38.0 / 43.0	65 / 45	55 / 40	200 / 200
2	27.0 / 33.3	25.1 / 36.0	70 / 55	70 / 50	200 / 150
3	28.0 / 30.0	28.0 / 32.0	68 / 58	70 / 51	200 / 150
4	23.0 / 32.4	24.4 / 32.7	80 / 50	100 / 70	50 / 150
5	20.1 / 26.0	20.5 / 26.0	84 / 70	95 / 80	150 / 150
6	28.0 / 33.7	29.4 / 36.7	65 / 50	70 / 55	200 / 150
7	22.6 / 30.0	24.8 / 32.0	92 / 77	90 / 77	200 / 100
8	23.1 / 31.8	24.0 / 33.4	92 / 72	100 / 75	100 / 300
9	23.5 / 28.8	23.1 / 29.0	93 / 80	100 / 90	100 / 200
10	21.5 / 26.1	21.0 / 24.3	93 / 80	100 / 90	100 / 100
11	26.0 / 34.0	24.4 / 31.0	90 / 64	100 / 84	200 / 200
12	23.9 / 31.2	22.5 / 33.0	93 / 66	87 / 60	200 / 250
13	22.5 / 37.9	22.5 / 36.0	90 / 60	93 / 70	200 / 150
14	24.1 / 34.5	22.5 / 36.9	93 / 69	75 / 49	100 / 300
15	23.3 / 38.8	23.0 / 36.8	91 / 52	97 / 53	50 / 300
16	24.8 / 33.8	23.4 / 29.9	89 / 66	89 / 49	100 / 200
17	24.6 / 32.7	24.8 / 31.4	96 / 72	85 / 50	100 / 200
18	24.9 / 32.7	24.1 / 30.8	93 / 69	87 / 75	100 / 250
19	22.8 / 30.3	21.8 / 31.1	85 / 60	86 / 72	100 / 200

Irrigation volume varied from 50 to 200 mL in the morning and from 100 to 300 mL in the evening. The morning mean was 139.47 mL, compared with 194.74 mL in the evening. Across all observations, 2.65 L was applied in the morning and 3.70 L in the evening, giving a total measured irrigation volume of 6.35 L. These values describe the recorded observation period only and are not extrapolated to the complete crop cycle.

3.2 Response-Time Result

Table 3: Individual sensor signal-detection response-time observations.

Trial	Signal-detection response time (s)
1	0.488
2	0.406
3	0.590
Mean ± SD	0.495 ± 0.092
Range	0.406–0.590

The three response-time observations were 0.488, 0.406, and 0.590 s. Their mean was 0.495 s with a sample standard deviation of 0.092 s and a range of 0.406–0.590 s. This result indicates relatively short signal-detection times during the three tests, but the small number of trials does not support a generalized performance claim.

4. DISCUSSION

Across 19 observation periods, morning conditions were generally cooler and more humid, with higher soil moisture than evening conditions. Irrigation volume also varied between observations. These descriptive patterns support the practical value of monitoring soil and environmental conditions, but they do not establish causation or an optimal irrigation quantity.

The measured 6.35 L represents water physically recorded during the 19 observation periods. It is not a seasonal water-use or water-saving estimate because the crop cycle was incomplete and no replicated control was available. Irrigation outcomes depend on crop, environment, and control strategy (Gaitan et al., 2025; Preite & Vignali, 2024).

The growth-stage framework is consistent with the stage-dependent crop water requirement principle in FAO-56 (Allen et al., 1998). However, its thresholds and durations are engineering assumptions rather than direct conversions of FAO crop coefficients. The current firmware did not use these stage-specific values to control the recorded irrigation events, so the framework requires validation before it can be described as an adaptive controller.

The hardware approach is consistent with low-cost smart irrigation research. Pereira et al. (2023) demonstrated ESP32-based drip irrigation, while Wanyama et al. (2024) discuss opportunities and constraints of smart irrigation in sub-Saharan Africa. The present work adds a crop-development-oriented control concept and live-crop observations.

The mean response time of 0.495 ± 0.092 s is based on only three readings and represents signal detection rather than complete environmental-change-to-pump latency. It is therefore an engineering observation, not a generalized latency specification.

The experimental design also limits the strength of inference. Five seedlings shared one prototype box, with no independent replicate boxes, randomized treatment assignment, or control. The current results should therefore guide system refinement rather than support claims of agronomic superiority.

5. CONCLUSION AND RECOMMENDATIONS

A growth-stage-oriented ESP32-based smart drip irrigation prototype was tested with five four-week-old bell pepper seedlings under pot conditions. Nineteen morning/evening observation periods produced 6.35 L of measured irrigation. Mean morning values were 24.48 °C air temperature, 24.59 °C soil temperature, 85.37% relative humidity, and 86.79% soil moisture, compared with 32.37 °C, 32.74 °C, 63.95%, and 65.26% in the evening. Three response-time readings gave 0.495 ± 0.092 s.

These findings show that the prototype acquired environmental measurements and delivered measurable irrigation under live-crop conditions. They do not establish seasonal water-use efficiency, water saving, or agronomic superiority. The growth-stage framework remains a design component requiring calibration and validation, and sensor accuracy evidence is limited.

The following steps are recommended: continue monitoring through the complete crop cycle; perform replicated sensor calibration; retain repeated response-time readings; evaluate the framework with independent experimental units and randomized treatments; compare it with a defined control before making water-saving claims; and validate the system at larger scale and under different soil and environmental conditions.

6. SUSTAINABLE DEVELOPMENT GOAL ALIGNMENT

The project aligns with six Sustainable Development Goals (SDGs). The alignment reflects the purpose and intended application of the engineering system and should not be interpreted as evidence that the present experiment measured progress against SDG indicators (United Nations, 2015).

SDG 2 – Zero Hunger: Supports sustainable and resilient food production through improved irrigation management for bell pepper.

SDG 6 – Clean Water and Sanitation: Supports more deliberate agricultural water management and the goal of improving water-use efficiency.

SDG 9 – Industry, Innovation and Infrastructure: Applies embedded control, sensors and automation to agricultural infrastructure.

SDG 12 – Responsible Consumption and Production: Encourages measured and controlled use of water as a production resource.

SDG 13 – Climate Action: Supports climate adaptation by improving irrigation monitoring under variable environmental conditions.

SDG 15 – Life on Land: Supports sustainable management of agricultural soil and water resources, particularly in water-limited environments.

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