

Design and Controlled-Plot Validation of a Smart Dual-Mode Irrigation System for West African Riverbank Farms

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ABSTRACT

Ewedu (*Corchorus olitorius*) is a nutritionally and economically vital leafy vegetable in West Africa, yet dry-season cultivation on riverbank plots remains constrained by manual, intuition-driven irrigation that is labour-intensive and agronomically imprecise. Existing smart irrigation systems are poorly suited to this setting, as they typically assume mains electricity, reliable internet, and technically skilled users conditions largely absent on West African riverbank farms. To address this gap, we designed, built, and field-tested a low-cost, solar-powered IoT irrigation system that uses real-time capacitive soil moisture monitoring to automate ewedu irrigation for smallholder farmers. The system integrates an ESP32 microcontroller running crop-specific hysteresis logic, a 12V DC pump and micro-sprinkler network powered directly from a solar-charged battery bank (eliminating the inverter stage), and a farmer-friendly web dashboard usable both online and offline. Gravimetric calibration of the moisture sensor achieved a mean R^2 of 0.975. Field testing established an irrigation hysteresis band of 22–25% volumetric water content (VWC) for pump activation and 35–38% VWC for deactivation. Over a 42-day trial, the solar subsystem maintained a mean battery state of charge of 50%, with no low-battery events, against average daily consumption of 40 Wh. A recruited farmer completed all seven user-acceptance tasks unaided, rating ease of use at 4.6/5. In a randomised two-zone trial, smart-irrigated plots yielded more than double the leaf fresh weight of manually irrigated controls (94.6 g vs. 44.8 g per plant, $p < 0.001$), alongside gains in dry weight and chlorophyll index, a 77% drop in disease incidence, and 33% less water use demonstrating substantial gains from context-aware, sensor-driven irrigation design.

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INTRODUCTION

Corchorus olitorius, known as *ewedu* in Yoruba-speaking communities and *ayoyo* in Hausa communities, is among the most culturally embedded and economically significant leafy vegetables in Nigerian, Ghanaian, and Beninese smallholder agriculture (Adebisi et al., 2013). The crop is nutritionally dense and provides a critical source of dry-season income, commanding stable market prices through periods when alternative vegetable crops are unavailable (Olaniyi et al., 2010). *Ewedu* cultivation is closely tied to riverbank and floodplain environments, where farmers exploit naturally elevated soil moisture during the dry season (Adeoti, 2008). In the absence of sensing or automation technology, irrigation scheduling on these farms is governed by experience and visual observation rather than objective soil moisture measurement (Namara et al., 2011).

Ewedu has a shallow root system and a narrow optimal soil moisture range approximately 60–80% of field capacity, or roughly 22–32% volumetric water content (VWC) on loamy riverbank soils that makes it acutely sensitive to both deficit and excess irrigation (Adebisi et al., 2013; Fasuyi, 2006). Under-irrigation reduces leaf area and marketable yield, while over-irrigation promotes root rot and soil-borne pathogens such as *Pythium* and *Fusarium* species (Olaniyi et al., 2010). Visually guided irrigation has been shown to deviate from optimal soil moisture on 60–75% of measurement occasions

in comparable subsistence vegetable systems (Kahimba et al., 2014).

The convergence of low-cost IoT sensing platforms (Nawandar & Satpute, 2019; Codeluppi et al., 2020) and increasingly affordable solar photovoltaic technology in sub-Saharan Africa (IRENA, 2022) creates a realistic opportunity to bring automated, data-driven irrigation to riverbank *ewedu* farms. However, the published smart-irrigation literature reveals a persistent mismatch between system design assumptions and the actual conditions of West African smallholder farming: most systems presuppose reliable internet connectivity, mains electricity, and technically literate users (Gutiérrez et al., 2014; Mehra et al., 2018), none of which reliably hold at the plot level on riverbank sites (Aker, 2011). No published system, to our knowledge, combines solar-only power, dual-mode (internet/offline) connectivity, and crop-specific calibration for *ewedu*.

This study addresses that gap. The specific objectives were to: (i) develop a real-time capacitive soil moisture sensing circuit; (ii) develop ESP32 firmware implementing *ewedu*-specific hysteresis irrigation logic; (iii) design and implement a standalone solar photovoltaic energy system; (iv) design a farmer-interactive web dashboard accessible in both internet and local intranet modes; and (v) validate system performance through sensor calibration, bench testing, and a field deployment trial including a randomised agronomic comparison against conventional manual irrigation.

MATERIALS AND METHODS

System Architecture

The system comprises five integrated subsystems: (1) a sensing subsystem of capacitive soil moisture sensors deployed at 10–15 cm depth in the ewedu root zone; (2) a processing subsystem based on an ESP32-WROOM-32 microcontroller (dual-core Xtensa LX6, 240 MHz, 18-channel 12-bit ADC, simultaneous AP/STA Wi-Fi) executing data acquisition, irrigation logic, web-server hosting, and network management; (3) an actuation subsystem consisting of a relay-switched 12 V DC submersible centrifugal pump (20 W, rated flow 13.33 L min⁻¹) and a PVC micro-sprinkler distribution network; (4) a standalone solar energy subsystem; and (5) a farmer-facing web dashboard served directly from the ESP32's flash memory. The pump connects directly to the 12 V battery bus with no inverter or AC stage anywhere in the system, eliminating inverter standby losses and an additional point of field failure.

Solar Photovoltaic Subsystem

Solar system sizing was based on a full daily load analysis (control electronics, sensors, and 1.5 h nominal pump operation), yielding a design daily energy demand of 81 Wh (85 Wh with margin). Using a conservative dry-season peak-sun-hour estimate of 5.2 h for the study region, this specified a 30 Wp monocrystalline panel; two units were installed in series to raise array voltage and reduce cable losses, producing a measured open-circuit voltage of approximately 44 V, within the 50 V input ceiling of the specified 10 A MPPT charge controller. The battery bank a single 12 V, 35 Ah unit was sized for two days of autonomy at 50% maximum depth of discharge, matching the pump's 12 V supply directly with no intermediate voltage conversion.

Firmware and Irrigation Control Logic

Firmware was developed in C++ (Arduino IDE, ESP32 Arduino Core) using WiFi.h, WebServer.h, Preferences.h (non-volatile parameter storage), ArduinoJSON.h, and esp_sleep.h. The irrigation controller implements a hysteresis-based threshold algorithm with ewedu growth-stage-specific setpoints (Table 1). On each measurement cycle, mean VWC across active sensor zones is compared against stored lower and upper thresholds: the pump activates below the lower threshold and deactivates above the upper threshold, with a minimum 90-second on-time to prevent relay short-cycling. All thresholds are farmer-adjustable

through the dashboard and persist in flash memory across power cycles.

Dual-Mode Network Architecture

On startup, the firmware attempts connection to a stored Wi-Fi network for 20 s. A successful connection places the system in internet (station) mode, serving the dashboard at the device's local IP with optional MQTT data publication. A failed connection automatically triggers access-point (offline intranet) mode, in which the ESP32 broadcasts its own Wi-Fi hotspot and serves the dashboard at a fixed local address (192.168.4.1). Mode switching is automatic and requires no farmer intervention; full dashboard functionality is retained in both modes, with only MQTT cloud logging and remote DDNS access unavailable offline.

Sensor Calibration

Capacitive sensors were calibrated gravimetrically against riverbank alluvial soil samples prepared at nine known VWC levels (0–45%). A linear regression of ADC output against gravimetric VWC ($VWC = a \times ADC + b$) produced site-specific calibration coefficients per sensor channel; channels with R^2 below 0.95 were replaced. A simplified two-point in-field recalibration procedure, guided through the dashboard, is also available for post-deployment sensor replacement.

Field Trial and Statistical Analysis

The system was deployed for a 42-day trial period spanning greenhouse-simulated dry-season conditions. A randomised block design compared an automated smart-irrigation zone against an adjacent zone under the farmer's conventional manual irrigation practice, both planted with the same ewedu variety, seed density, and planting date. Data collected included per-zone VWC at 15-minute intervals, daily pump operation timing, weekly leaf fresh and dry weight, SPAD chlorophyll index, disease incidence, and total water volume applied (estimated from rated pump flow and run time). Treatment effects were assessed by one-way analysis of variance (ANOVA) at $p < 0.05$. Separately, a recruited ewedu farmer completed a seven-task user-acceptance protocol (reading moisture data, identifying pump state, adjusting thresholds, manual override, sensor recalibration, and identifying network mode) without researcher assistance; task completion, errors, time-on-task, and perceived ease of use (five-point Likert scale) were recorded.

Table 1: Ewedu (*Corchorus olitorius*) Soil Moisture Threshold Parameters Implemented in the Irrigation Control Firmware, by Growth Stage

Growth Stage	Duration (DAP)	Lower Threshold (% VWC)	Upper Threshold (% VWC)	Agronomic Basis
Germination / Establishment	0–7	25	35	High moisture requirement for seed imbibition and radicle emergence
Early Vegetative	8–21	22	32	Root establishment; moderate moisture; avoid saturation
Active Vegetative (Harvest)	22–35+	22	30	Peak leaf production; consistent moisture critical for yield quality
Post-First-Harvest Ratoon	36+	20	30	Regrowth; slightly drier tolerance once root system established

RESULTS AND DISCUSSION

Results

Solar Photovoltaic System Performance

The series-wired panel configuration produced a measured array open-circuit voltage of approximately 44 V, consistent with two 22 V-Voc panels in series and within the MPPT controller's 50 V input ceiling. Battery state of charge

remained at a mean of 50% (range 42–61%) across the 42-day trial, with no low-battery cutoff events. Measured mean daily energy consumption was 40 Wh, modestly below the 81 Wh design ceiling, explained by an empirically tuned mean pump run-time of 22 min per day well under the 90-minute allowance conservatively budgeted at the design stage (Table 2).

Table 2: Comparison of Design-Stage Estimates and Field-Measured Solar System Performance Over the 42-Day Trial

Parameter	Design Estimate	Field Measured	Remark
Array open-circuit voltage	22 V (single panel)	44 V	Panels wired in series; within 50 V MPPT input limit
Battery state of charge	≥20% (50% max DoD)	Mean 50% (range 42–61%)	No low-SoC cutoff events in 42 days
Daily energy consumption	~81 Wh	40 Wh (mean)	Shorter empirically tuned pump run-time than budgeted
Mean daily pump run-time	90 min (design allowance)	22 min	Reflects field-tuned hysteresis band
Days at critical low SoC (<20%)	N/A	0 of 42	Confirms adequacy of panel/battery sizing margin

Sensor Calibration and Threshold Commissioning

Gravimetric calibration achieved a mean R^2 of 0.975 and mean RMSE of 2.2% VWC across sensor channels (Table 3), within the 3–8% tolerance identified as adequate for irrigation scheduling in the literature (Bogena et al., 2017) and consistent with recent low-cost capacitive sensor calibration benchmarks (Abdelmoneim et al., 2025). During commissioning, the literature-derived default thresholds

(Table 1) were widened slightly to a lower threshold of 22–25% VWC and an upper threshold of 35–38% VWC to accommodate an observed sensor noise band of approximately $\pm 2\%$ VWC that otherwise produced relay short-cycling near the threshold boundary. This field-tuned band maintained a 25–35% VWC target operating range and eliminated short-cycling for the remainder of the trial.

Table 3: Sensor Calibration Results by Zone: Reference ADC Readings, Linear Regression Coefficients (VWC = $a \times \text{ADC} + b$), R^2 , and RMSE

Zone	Dry ADC	Wet ADC	Slope (a)	Intercept (b)	R^2	RMSE (% VWC)
Zone 1	3120	1310	−0.0246	76.8	0.98	2.1
Zone 2	3085	1290	−0.0251	77.4	0.97	2.4

System Control and Automation Performance

Across the trial, the firmware logged 187 discrete pump activation events. Mean relay response time the interval between a VWC reading crossing the lower threshold and pump activation was 1.4 s, and no relay short-cycling was observed after threshold commissioning. The system operated in internet (station) mode for 71% of the trial and reverted automatically to offline access-point mode for the remaining 29%, corresponding to periods when the on-site hotspot was deliberately disabled to test offline fallback. Every recorded transition occurred without loss of irrigation control functionality or farmer intervention.

Farmer Interaction and Usability

The recruited ewedu farmer completed all seven user-acceptance tasks without researcher assistance (100% completion rate; Table 4), with a mean perceived ease-of-use rating of 4.6 of 5. The two recorded errors both occurred on first attempts at multi-step tasks (threshold adjustment, calibration wizard) and were self-corrected on a second attempt without intervention. Over the trial, the dashboard logged 34 threshold adjustments and 9 manual pump overrides, indicating active engagement with the system rather than passive reliance on default automation.

Table 4: User Acceptance Testing Results: Task Completion, Time-on-Task, Errors, and Perceived Ease of Use

Task	Completed	Time (s)	Errors	Ease of Use (1–5)
1. Read current soil moisture	Yes	8	0	5
2. Identify pump operating state	Yes	6	0	5
3. Change lower threshold (slider)	Yes	24	1	4
4. Activate pump manually	Yes	11	0	5
5. Deactivate pump manually	Yes	9	0	5
6. Sensor recalibration (wizard)	Yes	46	1	4
7. Identify current network mode	Yes	15	0	4

Agronomic Field Trial Results

Leaf fresh weight in the smart-irrigated treatment more than doubled that of the manually irrigated control (94.6 ± 8.3 g versus 44.8 ± 6.1 g per plant; +111%, $p < 0.001$), with corresponding increases in leaf dry weight (+107%, $p < 0.001$) and SPAD chlorophyll index (+37%, $p < 0.001$) (Table 5). Disease incidence was 77% lower under smart irrigation

(4.2% versus 18.5% of plants affected, $p = 0.012$), and mean VWC deviation from the optimal range was 73% smaller under automated control. Total water applied was 33% lower under smart irrigation (61.7 versus 92.4 L m^{-2} week $^{-1}$, $p = 0.004$), a saving achieved simultaneously with, rather than at the expense of, the yield increase.

Table 5: Agronomic Performance Comparison Between Manually Irrigated (Control) and Smart-Irrigated (Treatment) Ewedú Plots

Parameter	Manual (Control)	Smart Irrigation (Treatment)	% Change	p-value
Leaf fresh weight per plant (g)	44.8 ± 6.1	94.6 ± 8.3	+111%	<0.001
Leaf dry weight per plant (g)	5.4 ± 0.9	11.2 ± 1.3	+107%	<0.001

Parameter	Manual (Control)	Smart Irrigation (Treatment)	% Change	p-value
SPAD chlorophyll index	32.6 ± 3.1	44.8 ± 2.7	+37%	<0.001
Disease incidence (% plants affected)	18.5	4.2	-77%	0.012
Mean VWC deviation from optimal (pp)	9.8	2.6	-73%	<0.001
Water applied (L m ⁻² week ⁻¹)	92.4	61.7	-33%	0.004

Discussion

Solar Energy System Performance

Measured daily energy consumption (40 Wh) fell modestly below the design ceiling (81 Wh), reflecting the value of conservative sizing margins rather than over-design: the empirically tuned pump run-time (22 min day⁻¹) was well under the 90-minute allowance budgeted conservatively at the design stage. The paired 30 Wp panels and 35 Ah battery therefore retain a comfortable margin for this two-zone pilot, consistent with the broader literature recommendation that off-grid solar irrigation systems for smallholder African contexts be intentionally oversized to protect against consecutive low-irradiance days and battery degradation (Liang et al., 2024; Balamurali et al., 2025). The series-wired panel configuration producing 44 V rather than the single-panel 22 V assumed at the design stage illustrates a low-cost field adaptation that reduces cable losses without requiring a different controller specification, provided the controller's input voltage ceiling is respected.

Sensor Calibration and the Field-Tuned Irrigation Threshold

The calibration accuracy achieved (mean $R^2 = 0.975$, RMSE = 2.2% VWC) confirms that low-cost capacitive sensors, calibrated against site-specific gravimetric reference samples rather than generic manufacturer curves, can support threshold-based irrigation control on alluvial riverbank soils consistent with recent findings that site-specific calibration is the dominant factor separating usable from unreliable low-cost sensor deployments (Abdelmoneim et al., 2025). The modest widening of the operational hysteresis band during commissioning reflects a genuine trade-off between agronomic precision and mechanical durability: a narrower band tracks the literature-derived optimal moisture window more closely but increases relay switching frequency in the presence of sensor noise ($\pm 2\%$ VWC, observed empirically). The wider, field-commissioned band traded a small amount of agronomic precision for improved relay longevity, a trade-off also reported once laboratory-derived thresholds meet field-level sensor noise in other deployments (Nsah et al., 2024).

Network Resilience

The 1.4 s mean relay response time and absence of missed irrigation events across 187 logged cycles indicate reliable controller performance under continuous field operation. Of particular relevance to the design gap identified in the literature, the automatic and lossless transition between internet and offline access-point modes directly addresses the assumption of uninterrupted connectivity embedded in most published smart irrigation systems (Gutiérrez et al., 2014; Mehra et al., 2018), which are consequently non-functional on riverbank sites with intermittent mobile network coverage. Comparable dual-mode or edge-resilient architectures have begun to appear in recent smart-irrigation literature as connectivity is increasingly recognised as a first-order design constraint for smallholder deployment (Morchid et al., 2025; Duguma & Bai, 2025).

Farmer Usability and Technology Acceptance

The 100% unaided task completion rate and 4.6/5 ease-of-use rating provide direct empirical support for the Technology Acceptance Model prediction that perceived ease of use is a primary determinant of voluntary adoption among users with limited prior exposure to digital tools (Davis, 1989). The two first-attempt errors, both on multi-step interactions, align with the general finding that novice users require an initial orientation pass even on well-designed interfaces, with self-correction on a second attempt indicating adequate rather than deficient design (Medhi et al., 2011). The 34 threshold adjustments and 9 manual overrides logged over the trial suggest the farmer participant treated the dashboard as an active management tool rather than a passive display.

Agronomic Outcomes

The agronomic results are the most consequential finding of this study. A more-than-twofold increase in leaf fresh weight under automated irrigation is substantially larger than the 25–45% water-productivity gains typically reported for solar-powered but non-sensor-driven irrigation systems in the sub-Saharan African literature (Aliyu et al., 2018). This magnitude is more plausibly explained by two effects operating simultaneously but rarely combined in prior deployments: correction of the moisture deficit that constrains manually irrigated plots for a substantial fraction of the growth cycle (consistent with Kahimba et al., 2014), and avoidance of the over-irrigation and associated disease pressure that afflicts manually irrigated plots at the opposite end of the moisture range, reflected in the 77% reduction in disease incidence. Because manual irrigation in this trial oscillated across both failure modes rather than being uniformly deficient or excessive, an automated system correcting both simultaneously would be expected to produce larger gains than a system addressing water scarcity alone the typical framing in the existing solar irrigation literature (Balamurali et al., 2025). The concurrent 33% reduction in water applied is consistent with reductions reported in comparable precision vegetable irrigation studies (Pereira et al., 2010; Parra-López et al., 2025) and extends the deficit-irrigation evidence available for related jute mallow genotypes (Mgolozeli et al., 2022), suggesting that real-time sensor-driven scheduling can achieve a larger simultaneous water saving and yield gain than a fixed deficit-irrigation regime.

Limitations

Several limitations qualify these findings. The field trial was conducted over a single 42-day season in a controlled greenhouse-simulated plot rather than an open riverbank site, so wind exposure, pest pressure, and inter-annual solar irradiance variability were not captured. User acceptance testing involved a single farmer participant; usability findings should be treated as preliminary pending a multi-participant, multi-site study. The agronomic and system trial was conducted at a two-zone pilot scale; scaling to a multi-zone commercial riverbank farm has not yet been empirically confirmed, though the energy budget margin observed here is

encouraging. Formal cost-benefit and household income analysis was outside the scope of this study.

CONCLUSION

This study designed, developed, and field-evaluated a low-cost, solar-powered, IoT-based smart irrigation system using real-time soil moisture monitoring to automate ewedu irrigation on smallholder riverbank farms. All five design objectives were met: a capacitive soil moisture sensing circuit was developed and calibrated to a mean R^2 of 0.975; ESP32 firmware implementing ewedu-specific hysteresis irrigation logic operated reliably across 187 field-logged cycles; a standalone solar photovoltaic system sustained continuous operation without a single low-battery event over 42 days; a farmer-interactive, dual-mode web dashboard achieved a 100% unaided task completion rate in user acceptance testing; and system performance was validated through both calibration experiments and a randomised field trial in which smart-irrigated ewedu plots produced more than double the leaf fresh weight of manually irrigated controls while using approximately one-third less water. These results indicate that automated, sensor-driven irrigation control, when designed explicitly around the energy, connectivity, and literacy constraints of West African riverbank smallholder farming, can deliver agronomic improvements substantially larger than those reported for solar irrigation systems that address water delivery alone. Priority directions for further work include open-site, full-season field validation; multi-participant usability testing; multi-zone scale-up trials; integration of soil salinity sensing; and formal cost-benefit analysis to quantify return on investment for smallholder adopters.

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