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Adaptive State-of-Charge–Driven Energy Management with Rain-Responsive Irrigation for Solar-Powered Multicrop Hydroponics in Tropical Islands

Muji Juherwin[a], Mohamad Farid Misnan[b,c*] & Sakhiah Abdul Kudus[d]

[a]*Energy System Engineering Study Program, Lombok Institute of Technology, West Nusa Tenggara, 83662, Indonesia.*

[b]*Smart Manufacturing Research Institute (SMRI), Universiti Teknologi MARA Shah Alam 40450, Selangor, Malaysia.*

[c]*Faculty of Electrical Engineering, Universiti Teknologi MARA Shah Alam 40450, Selangor, Malaysia.*

[d]*Faculty of Civil Engineering, Universiti Teknologi MARA Shah Alam 40450, Selangor, Malaysia.*

**Corresponding author: mohamadfarid@uitm.edu.my*

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ABSTRACT

This study addresses the need for resilient, off-grid food production on tropical islands by integrating renewable energy management with outdoor hydroponic cultivation. The objective of the research was to design and field-validate an adaptive energy balance controller that coordinates energy availability and water management using real-time measurements of battery state of charge (SoC) and rainfall–runoff signals. The proposed system comprised a photovoltaic array, a battery energy storage unit, low-cost environmental and electrical sensors, and an embedded microcontroller executing a supervisory control policy. SoC was estimated from voltage and current measurements with signal conditioning to stabilize noisy data, enabling rain-aware irrigation prioritization during daylight hours and SoC-dependent duty cycling during nighttime operation. Using 5-minute averaged data, the SoC estimation achieved a mean absolute error of 1.207% and a root mean square error of 1.689%, corresponding to estimation accuracies of 98.79% and 98.31%, respectively. Field trials on a nutrient film technique hydroponic system in East Lombok, Indonesia, under sunny, cloudy, and rainy conditions demonstrated that SoC was maintained above a conservative safety margin, recovering during daylight periods and declining in a controlled manner overnight. Rainfall–runoff detection suspended irrigation for extended durations, with brief circulation intervals to maintain root oxygenation, thereby reducing water consumption and limiting nutrient dilution. Nighttime duty cycling aligned pump operation with available stored energy, avoiding deep discharge and supporting battery health. Time-series analysis confirmed autonomous responses without manual intervention.

Keywords: Adaptive state-of-charge control; solar-powered hydroponics; rain-responsive irrigation; off-grid energy management; tropical island agriculture

INTRODUCTION

Sustainable agriculture has become a central priority for governments, practitioners, and researchers seeking resilient food systems that can operate with limited resources and under increasingly variable climatic conditions (Kabato et al. 2025; Katel et al. 2022; Srivastav et al. 2021). Off-grid production models that integrate renewable energy with controlled-environment cultivation offer a promising pathway, particularly for tropical island contexts where solar potential is high but infrastructure and supply chains may be fragile (Majeed et al. 2023; Rahman et al. 2022; Augustyn et al. 2021). Within this landscape, hydroponics a soilless cultivation method using nutrient solutions has gained traction because it can produce high yields with relatively low water use and precise nutrient management, making it well suited to land-constrained or soil-degraded sites (Elseedy et al. 2025; Alizaeh et al. 2025; Pomoni et al. 2023). For Indonesia and comparable archipelagic settings, the alignment between solar resource availability, food security needs, and the potential of hydroponic production is particularly compelling (Fitralisma et al. 2025; Siregar et al. 2024; Kurnianto 2024; Imtihan et al. 2024). Proof-of-concept and early field deployments already indicate that solar energy can effectively power greenhouse and open-air agri-systems, including hydroponics and aquaponics, provided that system-level controls are carefully designed (Wong et al. 2026; Zulkifli et al. 2025; Bakar et al. 2022). Recent developments have further expanded hydroponic practice toward multicrop configurations, enabling the simultaneous cultivation of leafy vegetables with differing growth characteristics (Olasehinde 2025; Ahn et al. 2022).

Despite this promise, translating solar-powered hydroponics from concept to robust field operation remains challenging. Hydroponic techniques can outperform conventional soil-based systems, but only if water, nutrients, and energy inputs are tightly regulated at the right time scales (Sousa et al. 2024; Rajendran et al. 2024; Sambo et al. 2019; Chaiwongsai 2019; Sharma et al. 2018). In tropical islands, rapid swings in irradiance due to cloud cover and convective storms complicate energy budgeting and pump scheduling, while intense rainfall events risk nutrient dilution if irrigation continues unchecked (Gao et al. 2024; Han et al. 2024; Ghiasi et al. 2023; Roy et al. 2022). Furthermore, ensuring reliability in remote sites requires low-cost, durable sensing and control that can withstand humidity, heat, and intermittent connectivity, without relying on continuous human intervention (Callebaut et al. 2021; Sunny et al. 2020).

The principal research problem addressed in this study is how to maintain stable, efficient, and autonomous operation of an outdoor hydroponic system when the energy source is intermittent and the environment is highly variable. Solar-powered systems must cope with diurnal and weather-driven variability in generation, while safeguarding the health and lifetime of the storage subsystem. Lead–acid batteries, still common in cost-constrained deployments, are particularly sensitive to deep discharges and aggressive cycling; poor energy management accelerates aging and increases failure risk (Jeevarajan et al. 2022; Ruetschi, 2004). In this regard, Ahamad et al. (2025) similarly emphasized that effective energy management strategies and informed decision-making frameworks are critical success factors for ensuring the sustainability and long-term viability of solar energy systems in Malaysia. In parallel, irrigation scheduling that ignores rainfall can squander energy and degrade nutrient solution quality, undermining plant performance. Hence, the overarching challenge is not merely energy management or irrigation control in isolation, but the coordinated control of both domains in real time under field conditions (Etukudoh et al. 2024; Orikpete et al. 2023; Misnan et al. 2022).

General solutions proposed in the literature include oversizing photovoltaic arrays and storage, deploying higher-fidelity forecasting to anticipate irradiance fluctuations, or adopting conservative static schedules for pumps and ancillary loads (Gao et al. 2024; Sengupta et al. 2024; Ghiasi et al. 2023). While these approaches can improve reliability, they entail trade-offs: oversizing raises capital costs and may still underperform during prolonged cloudy periods; forecast-dependent strategies require data and communications that may be unavailable or unreliable in remote islands; and fixed schedules are inherently inefficient because they fail to exploit periods of surplus energy and do not respond to sudden rainfall. As a result, there is a strong rationale for embedded controllers that adaptively reconcile energy availability, storage health, and water management in situ.

More specific strands of prior work suggest promising building blocks. Research on solar agrisystems and smart irrigation emphasizes the utility of environmental sensing rain, flow, and light to trigger context-aware irrigation policies that curb water waste and protect nutrient concentrations (Parajuli et al. 2023; Novaldo et al. 2022; Bakar et al. 2022; Chaiwongsai 2019). In parallel, the renewable-energy and power-systems literature highlights the importance of state-of-charge-aware load management to protect batteries and align demand with supply (Demirci et al. 2024; Sorouri et al. 2024; Afshar et al. 2024; Cao et al. 2024). Together, these threads point toward a supervisory logic that should throttle or defer non-critical loads as SoC falls, while responding immediately to rainfall by altering irrigation duty cycles.

Technical advances in low-cost microcontrollers and sensing further enable such integration. Affordable DC power sensing (e.g., INA219) combined with voltage measurements supports real-time SoC estimation at the edge, especially when augmented by simple signal conditioning such as exponential moving averages to stabilize noisy measurements (Demirci et al. 2024; Sorouri et al. 2024). Light-dependent resistors can serve as a robust proxy for day–night mode switching, and basic flow/rain detectors provide timely runoff cues without the burden of complex instrumentation (Bakar et al. 2022; Chaiwongsai 2019). For rural deployments, these components can be packaged into resilient PVC and polymer hardware float valves, backflow lines, and overflow drains that not only simplify installation and maintenance but also reduce the risk of nutrient contamination during storms (Orikpete et al. 2023; Misnan et al. 2022).

Even so, a targeted synthesis of these elements for open-air hydroponics in tropical islands remains limited in the literature. Hydroponics research has focused extensively on nutrient delivery optimization, crop performance, and greenhouse automation, but comparatively fewer field-validated studies demonstrate a controller that is simultaneously SoC-adaptive and rain-aware in a non-greenhouse setting (Sousa et al. 2024; Rajendran et al. 2024; Sambo et al. 2019; Sharma et al. 2018). Energy-management studies, conversely, often evaluate SoC algorithms or microgrid strategies without coupling them to water-management dynamics or to the agronomic outcomes of hydroponic systems (Gao et al. 2024; Demirci et al. 2024; Sorouri et al. 2024; Afshar et al. 2024; Cao et al. 2024; Ghiasi et al. 2023). Field-scale alignments of these domains are especially scarce for Indonesia and similar island contexts, where the combination of high rainfall intensity, intermittent irradiance, and constrained budgets complicates control design (Siregar et al. 2024; Kurnianto 2024; Imtihan et al. 2024).

Accordingly, this study proposes and evaluates an SoC-based adaptive energy balance control integrated with rain-runoff detection for an outdoor, solar-powered hydroponics system. The approach builds on existing SoC-aware control and smart irrigation ideas but consolidates them into a single, low-cost embedded framework tailored to the constraints of tropical island environments. Specifically, the controller estimates SoC from voltage and current signals, applies smoothing to enhance decision stability, and enforces a conservative SoC threshold to protect battery health, consistent with the reliability imperatives of lead–acid storage (Jeevarajan et al. 2022; Ruetschi 2004). In parallel, rainfall sensing and flow detection are employed to suspend or modulate irrigation during precipitation events in order to prevent nutrient dilution and unnecessary energy expenditure (Parajuli et al. 2023; Novaldo et al. 2022; Bakar et al. 2022). The system is implemented on an ESP32 platform and coupled with simple physical safeguards, including float valve regulation, overflow routing, and backflow protection, so that both energy and water subsystems respond coherently to rapidly changing environmental inputs (Orikpete et al. 2023; Misnan et al. 2022).

The aim of this research is to develop and field-validate an autonomous, low-cost control framework that integrates state-of-charge–adaptive energy management with rain-responsive irrigation for outdoor, solar-powered hydroponics in tropical island contexts. This aim is pursued through the design and implementation of a practical SoC-adaptive controller using commodity sensors and embedded hardware, the integration of rain-runoff detection and associated mechanical safeguards to actively coordinate irrigation with rainfall events, and experimental validation through field testing in Indonesia using a multicrop hydroponic configuration comprising Brassica sp., Ipomoea aquatica, and Apium graveolens, with emphasis on energy reliability, pump behavior, and water-use implications under variable weather conditions (Majeed et al. 2023; Ghiasi et al. 2023; Rahman et al. 2022). The novelty of this work lies in the tight coupling of SoC-aware energy management and rain-aware irrigation within an empirically tested, off-grid hydroponic platform. The scope encompasses controller design, sensing and actuation architecture, and experimental evaluation under real tropical conditions, without addressing crop physiology optimization or advanced forecasting, which are identified as promising avenues for future work. By demonstrating that a low-cost, embedded controller can jointly manage energy and water in a volatile environment, this study contributes a replicable template for sustainable food production in island regions, bridging gaps between renewable-energy control, hydroponic automation, and practical field deployment (Rajendran et al. 2024; Gao et al. 2024; Ghiasi et al. 2023; Sambo et al. 2019).

METHODOLOGY

This study adopted an experimental field approach to develop, implement, and evaluate a state-of-charge adaptive energy balance controller integrated with rain-runoff management for an outdoor, solar-powered hydroponics system. The design philosophy prioritized the use of low-cost, robust components and edge-level computation appropriate for tropical island environments characterized by variable irradiance and intense rainfall (Sengupta et al. 2024). The methodology was structured into three main phases: (i) system architecture definition and control algorithm development, (ii) prototype construction and on-site deployment, and (iii) multi-day field validation under naturally varying weather conditions.

The prototype was deployed outdoors in the Lenek District, East Lombok (West Nusa Tenggara, Indonesia), a tropical region marked by distinct wet–dry seasons and rapid cloud variability. The cultivated crops comprised Brassica sp., Ipomoea aquatica, and Apium graveolens, grown in a dual-channel nutrient film technique (NFT) system to ensure continuous nutrient supply and to evaluate controller performance under realistic horticultural loading conditions (Sambo et al. 2019). Field testing was conducted over multiple days to capture sunny, cloudy, and rainy scenarios, allowing observation of day–night transitions and storm events that are central to the research problem (Sengupta et al. 2024).

SOLAR-POWERED OUTDOOR HYDROPONICS SYSTEM

The power train comprised a 160 Wp photovoltaic (PV) array, charge regulation, and a 12 V 200 Ah li-ion battery bank. Li-ion storage was selected for its cost-effectiveness, availability, and tolerance to rural conditions, while recognizing the need to avoid deep discharge to mitigate aging (Ruetschi, 2004). The overall interaction among PV, storage, loads, and supervisory control is summarized in the system block diagram (Figure 1) (Parajuli et al. 2023; Novaldo et al. 2022).

Figure 1 depicts the functional interactions between energy and water subsystems. Solar PV modules feed the charge regulator and 12 V battery bank; the ESP32 reads voltage and current from the storage node, derives SoC, and issues actuation signals to the pump relay. Environmental sensors rain, flow, and LDR feed the controller with real-time cues: (i) rain/flow for runoff detection, (ii) LDR for day/night mode switching. Mechanical safeguards (float valve, overflow outlet, backflow line) form a hydraulic protection loop that operates in concert with electronic control. Arrows in the diagram indicate (a) energy flow from PV to storage to loads and (b) information flow from sensors to controller to actuators, clarifying that decision-making is centralized in the ESP32 while safety is shared with passive plumbing.

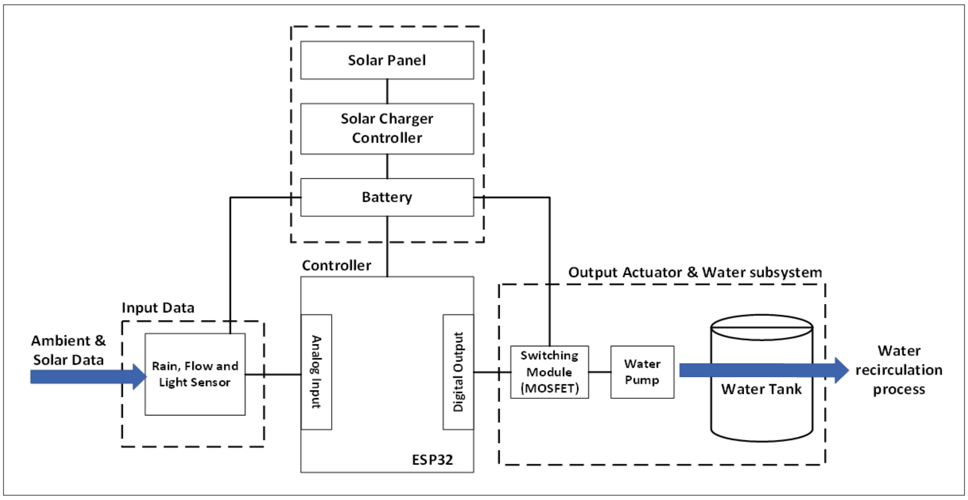

FIGURE 1. System architecture illustrating the interaction between energy supply, sensing, control, and water recirculation subsystems in the solar-powered hydroponic platform

SOC-ADAPTIVE CONTROL SYSTEM

The reservoir pumping operation is governed by an SoC-based adaptive energy balance control algorithm, which regulates water pumping by allocating energy according to real-time SoC measurements and the instantaneous availability of stored energy. The SoC level is determined within the microcontroller using the following simplified method:

$$SoC = \frac{V - V_{min}}{V_{max} - V_{min}} \times 100\% \quad (1)$$

where V is the terminal voltage of the battery, expressed in volts (V). V_{min} is the minimum battery voltage, dubbed the fully discharged state (0% SoC), while V_{max} indicates a fully charged state (100% SoC) of the battery's maximum voltage. The formula provides a measure of battery voltage relative to its operating limits and expresses SoC in percent.

Variations arising from charging and discharging cycles may prevent the direct estimation of an accurate SoC value. Nevertheless, the voltage-based SoC estimation method offers an effective mechanism for battery protection, as it disables pumping operations when the reported SoC falls below 55%. The selection of a 55% SoC threshold provides a protective margin to preserve battery health and ensure overall system reliability. Prolonged operation below this level may accelerate battery degradation and reduce service life. In addition, maintaining an SoC buffer above 55% enables the system to accommodate unforeseen increases in energy demand or extended periods of reduced solar irradiance, thereby supporting uninterrupted operation of critical functions such as nutrient pumping. SoC determination using characteristic parameters is carried out concurrently in this study, as these parameters are based on the open-circuit voltage and internal resistance characteristics of the battery, as modified.

The system autonomously regulates pump operation by switching it on and off at predefined intervals, while electrical energy is simultaneously generated by the solar panels. As a result, the battery voltage varies over time. The magnitude of these voltage fluctuations is governed by the internal resistance of the battery system, which can be expressed as:

$$R_{int} = \frac{V_{no\,load} - V_{load}}{I_{load}} \quad (2)$$

R_{int} is to be measured in ohms (Ω) and defined by the value of voltage drop concerning its power used. V_{noload} is referred to as the battery's no-load or open-circuit voltage (V), which represents the battery's voltage when no current is drawn. V_{load} is referred to as loaded voltage (V), which represents a battery's voltage with a load connected such that the current flows. I_{load} is a load current in amperes (A) that refers to the current drawn by the load provided to the system. The equation determines internal resistance by calculating the difference in the no-load voltage and loaded voltage over the current drawn. It is one of the factors to use in smoothing out the voltage value for analysis. The smoothed estimate of the voltage value is the one used for calculating SoC for analysis.

$$V_{corrected} = V + (I \times R_{int}) \quad (3)$$

In this manner, the objective is to follow the required dynamics during the experiment. Therefore, the SoC was calculated using the exponential moving average (EMA) of the value of voltage. The EMA of the voltage at time, t is given by:

$$V_{EMA_t} = \alpha\, x_t + (1 - \alpha)\, V_{EMA_{t-1}} \quad (4)$$

where V_{EMAt} is the value of the exponential moving average of voltage at time t, x_t is the latest value of voltage, V_{EMAt-1} is the previous value of VEMA, and α is the smoothing factor, which determines the weight given to recent observations and is calculated as:

$$\alpha = \frac{2}{N+1} \quad (5)$$

where N represents the selected window size or period for smoothing. The EMA helps reduce fluctuations in voltage measurements, providing a more stable representation of SoC dynamics over time

The SoC-based adaptive strategy ensures efficient energy utilization while preventing excessive battery discharge. The control algorithm operates by acquiring real-time data on SoC, available solar energy, and the energy requirements of the hydroponic system. Energy is then distributed according to system demand, ensuring that essential functions remain operational even under limited energy availability. To enhance operational efficiency, a rain sensor is incorporated to automatically regulate water pumping, thereby reducing unnecessary irrigation and minimizing water wastage during rainfall events. In addition, the algorithm dynamically adjusts power delivery to various subsystems to achieve an optimal balance between energy supply and demand, which contributes to extending battery operating duration. The overall control logic and feedback structure of the algorithm are illustrated in the flowchart shown in Figure 2.

The flowchart depicts an automated hydroponic pumping system governed by an adaptive feedback control mechanism. The sequence begins with the initialization of digital pins for relay actuation and the definition of key variables, including rain detection, ambient light, and battery SoC. The system continuously monitors inputs from the rain sensor, light-dependent resistor (LDR), and voltage sensor to obtain environmental and battery status information. The control logic first evaluates the presence of rainfall; when rain is detected, all water pumps are deactivated to prevent excessive irrigation and conserve water resources. In the absence of rainfall, the algorithm assesses daylight conditions. If sufficient daylight is present, all water pumps are activated to support irrigation. When daylight is unavailable, the battery SoC is evaluated; if the SoC falls below 55%, the pumps operate in an energy-saving mode, running for two minutes followed by a ten-minute pause to preserve battery capacity. This closed-loop feedback process continuously adapts to changes in environmental conditions, maximizing the efficiency of both battery usage and water consumption. Through adaptive energy management and rain-aware control, the system supports sustainable, autonomous, and scalable hydroponic operation.

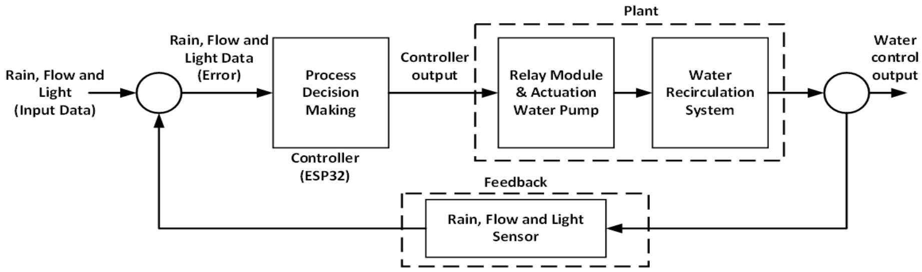

FIGURE 2. Control logic and closed-loop feedback structure of the proposed SoC-adaptive and rain-responsive irrigation control system

RAIN PROTECTION SYSTEM

The rain protection system is designed to regulate rainwater drainage efficiently, preventing excess water from disrupting the operational balance of the outdoor hydroponic system. The primary components of the system include an automatic valve that controls water inflow into the nutrient reservoir, a rainwater collection mechanism, and a rainwater runoff detection module.

RAINWATER RUNOFF DETECTION

Rainfall can significantly influence nutrient solution concentration in outdoor hydroponic systems; therefore, a flow sensor is employed to detect both the presence and volume of rainwater runoff. A water collector is positioned to capture runoff from the surface of the solar panels, thereby ensuring reliable and accurate detection. This configuration serves two primary purposes: to ensure that the collected water volume is sufficient for precise flow sensor operation and to provide early indication of excess rainfall runoff that may enter the hydroponic system.

The justification for collecting runoff from the solar panels lies in the fact that the initiation of water flow from the panel surfaces indicates accumulating precipitation that could potentially reach the hydroponic installation. Early identification of such runoff enables timely control actions to regulate water inflow and prevent unintended dilution of the nutrient solution, thereby maintaining optimal conditions for plant growth.

EXCESS WATER CONTROL

A backflow prevention mechanism is implemented using a nutrient return pipe equipped with a drain hole to mitigate dilution of the nutrient solution caused by rainfall ingress. Excess rainwater is discharged before reaching the nutrient reservoir, thereby preventing unwanted water from contaminating the nutrient solution. When the flow sensor detects additional rainwater runoff, all pumps are automatically deactivated, allowing the remaining nutrient solution within the hydroponic channels to drain back into the nutrient bucket. This arrangement prevents system overfilling while maintaining the nutrient concentration required for optimal plant growth.

From a mechanical standpoint, a ball-type automatic valve is employed to regulate water inflow into the nutrient bucket in conjunction with the drain hole. Under normal operating conditions, the valve remains open provided that the collected rainwater volume does not exceed a predefined limit, allowing the hydroponic system to function as intended. When the accumulated rainwater surpasses this threshold, the floating ball mechanism actuates valve closure, thereby preventing further entry of non-nutrient water into the system. This design helps minimize nutrient solution imbalance during periods of heavy rainfall.

IMPLEMENTATION

A solar-powered outdoor hydroponics system prototype was constructed and tested in a real-world setting to validate the proposed layout. The experiment was configured with a photovoltaic system of renewable resources with a capacity of 12 V 160 Wp, which provides an uninterrupted power supply. A 12 V 200 Ah li-ion battery bank handles energy storage and dispatching. The pumps that service the hydroponic subsystems are powered exclusively by electrical energy, and energy monitoring sensors are employed to enhance resource optimization. For autonomous control, SoC, solar irradiation, and rainwater runoff sensor data are measured and processed by an ESP32 microcontroller executing an SoC-based control algorithm. The system was installed in the tropical outdoor environment of Lenek District, East Lombok, West Nusa Tenggara, a region characterized by a tropical climate with distinct wet and dry seasons. The hydroponic system employed was a Nutrient Film Technique (NFT) configuration consisting of two parallel channels supporting the cultivation of Brassica sp., Ipomoea aquatica, and Apium graveolens. This setup enabled evaluation of the system's energy management efficiency, responsiveness to changing solar irradiance, and robustness under variable weather conditions.

RESULTS AND DISCUSSION

This section consolidates the results obtained from the field deployment of the SoC-based adaptive energy balance control applied to a solar-powered outdoor hydroponics system on a tropical island. It presents the system implementation outcomes, quantifies controller performance under rainfall events and day–night operating transitions, and evaluates the interactions between battery behavior and irrigation control in relation to the study objectives. These objectives include maintaining the battery state of charge (SoC) above a conservative safety threshold, mitigating nutrient dilution during precipitation, and ensuring autonomous operation under conditions of rapidly fluctuating irradiance and rainfall (Demirci et al. 2024; Sorouri et al. 2024; Parajuli et al. 2023; Novaldo et al. 2022; Ruetschi, 2004).

SYSTEM IMPLEMENTATION

The prototype incorporates hydraulic protection mechanisms, environmental sensors, SoC estimation, and an ESP32-based supervisory control system to enable real-time coordination of energy and water management. The subsequent subsections outline the key hardware components and control features before presenting the quantitative analyses.

SYSTEM OVERVIEW AND PHYSICAL IMPLEMENTATION

This subsection introduces the passive hydraulic safeguards employed to maintain reservoir stability and nutrient integrity under open-air conditions. The assembly is designed to regulate inflow during precipitation, prevent overflow and backflow, and facilitate controlled drainage for maintenance without disrupting hydroponic circulation.

Figure 3 illustrates the nutrient distribution and recirculation system of the outdoor NFT hydroponic installation. The system consists of a nutrient reservoir (nutrition bucket), a supply hose that delivers nutrient solution from the water pump to the NFT channels, and a return line that directs excess nutrient solution back to the reservoir. This closed-loop configuration enables continuous circulation while maintaining a stable nutrient volume during operation.

The hydroponic system is configured for multicrop cultivation (*Brassica sp*., *Ipomoea aquatica*, and *Apium graveolens*) and equipped with a UV filtration unit. UV filtration is widely recognized as an effective method for suppressing microbial proliferation and biofilm formation in recirculating hydroponic systems, particularly when multiple crop species share a common nutrient solution. The implementation of UV treatment enhances nutrient solution hygiene without introducing additional mechanical regulation components that may increase system complexity or maintenance demands.

The nutrient return line directs excess solution back to the reservoir, preventing uncontrolled discharge and minimizing nutrient loss. All hydraulic components are constructed using PVC tubing and fittings, ensuring mechanical robustness, ease of installation, and durability under outdoor tropical conditions. Nutrient stability and dilution control are achieved through active pump scheduling and rain-responsive irrigation logic implemented at the controller level, allowing the system to adapt to fluctuating environmental conditions while maintaining reliable nutrient circulation.

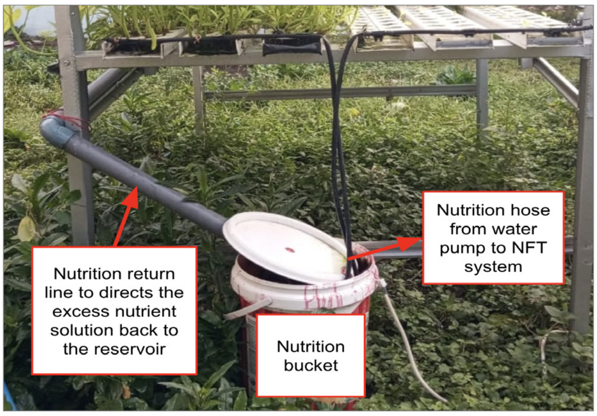

FIGURE 3. Overview of the nutrient circulation subsystem in the nutrient film technique (NFT) hydroponic installation

Figure 4 presents the planted NFT hydroponic system configured for multicrop cultivation in an outdoor environment. The system accommodates three vegetable species, namely *Ipomoea aquatica, Brassica sp.,* and *Apium graveolens*, which are cultivated simultaneously within the same NFT channels. A UV light filter is integrated into the nutrient circulation loop to suppress microbial growth and maintain nutrient solution hygiene, which is particularly important in shared, recirculating systems supporting multiple crop species.

The NFT hydroponics system provides a thin, continuous flow of nutrient solution along the plant roots, ensuring efficient nutrient uptake while minimizing water usage. The visual arrangement highlights the physical integration of crop placement, nutrient delivery, and filtration within a compact structure suitable for solar-powered operation in tropical conditions. This configuration supports uniform nutrient distribution and stable root-zone conditions, which are critical for sustaining plant growth under variable outdoor environments.

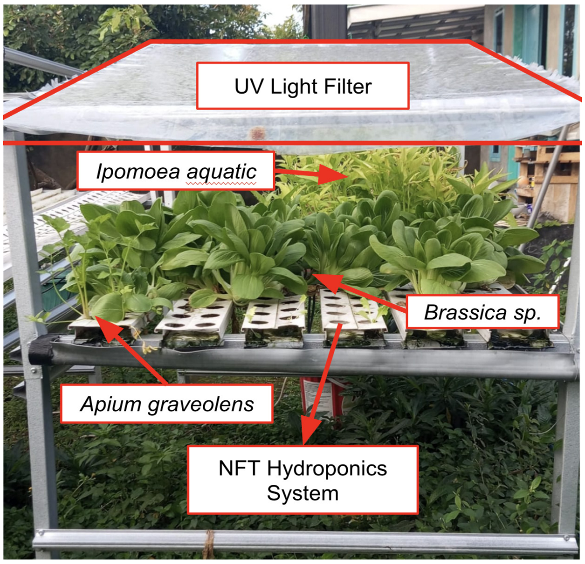

FIGURE 4. Field deployment of the solar-powered NFT hydroponic system showing multicrop cultivation, UV light filtering, and nutrient circulation layout

SENSORS AND MICROCONTROLLER ESP32

Figure 5 illustrates the sensor-integrated control architecture employed in the solar-powered outdoor hydroponics system. The system is centered on an ESP32 microcontroller, which functions as the primary processing and decision-making unit for energy management and irrigation control. The photovoltaic module supplies renewable energy, while the solar charger controller and Li-ion battery regulate energy storage and distribution to ensure continuous operation.

System operation is governed by State of Charge (SoC)-based control, where energy availability is monitored using a combination of voltage and power sensors, enabling more reliable SoC estimation without reliance on ACS712 current sensing. A MOSFET-based power switch replaces conventional relay modules, providing faster switching response, lower losses, and improved durability for frequent pump control cycles.

Environmental awareness is achieved through multiple sensors, including a light sensor (LDR) to distinguish day–night operation modes, a rainwater flow sensor to detect rain-induced water movement, and voltage sensing to assess battery status. When rainfall is detected, the controller adaptively disables the nutrient pump to prevent dilution of the nutrient solution. This integrated sensing and control strategy enables autonomous, energy-aware operation while maintaining nutrient stability and protecting system components under rapidly changing tropical weather conditions.

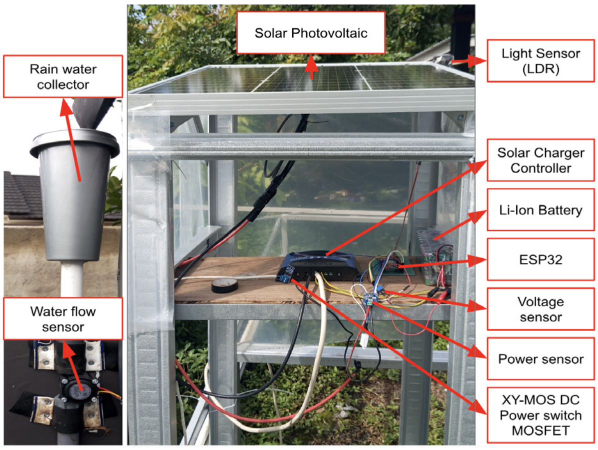

FIGURE 5. Integration of sensing, control, and power components for SoC-based adaptive energy balance control in the solar-powered outdoor hydroponic system

RAIN DETECTION VS. PUMP STATUS

Effective water resource management is essential in hydroponic and irrigation systems to prevent oversaturation and enhance overall efficiency. The system integrates a rain detection mechanism that employs a flow sensor to identify rainwater runoff, thereby regulating water pump operation. During daytime operation (08:00–16:00), the pump follows a modified control strategy in which it is deactivated for 10 minutes upon runoff detection, then reactivated for 2 minutes before reassessing runoff conditions. This repetitive control cycle ensures sufficient nutrient delivery to plants while reducing unnecessary water consumption during rainfall events.

Figure 6 shows the relationship between the intensity of rain and the status of the pump, illustrating system behavior in response to environmental conditions in real time. The black line illustrates the rainfall intensity, while the green line shows the pump's ON/OFF status. According to the system's logic, when rainwater runoff is detected, the pump is switched OFF for 10 minutes, then automatically turned ON for 2 minutes. This cycle repeats while rainwater runoff continues to be detected to avoid unnecessary irrigation during rainfall. It can be seen from the graph that in the timeframe of significant rainfall, which takes place between approximately 11:00 AM and 12:30 PM, the pump is detected to be OFF most of the time because of abundant runoff. In the absence of rainwater runoff for over 10 minutes, however, the system then resumes normal operations for nutrient augments. For daytime operation, the pump behaviour ignores the SoC and aims only at using the water efficiently, controlled by rainfall. It helps in preventing over-irrigation while assuring that nutrient levels are adequate during breaks in rainfall, which helps sustain efficient water management (Parajuli et al. 2023; Novaldo et al. 2022). The rain-aware policy reduces water and energy use during precipitation and protects nutrient concentration by interrupting flow when dilution risk is highest; brief ON windows maintain root oxygenation, balancing conservation with plant health.

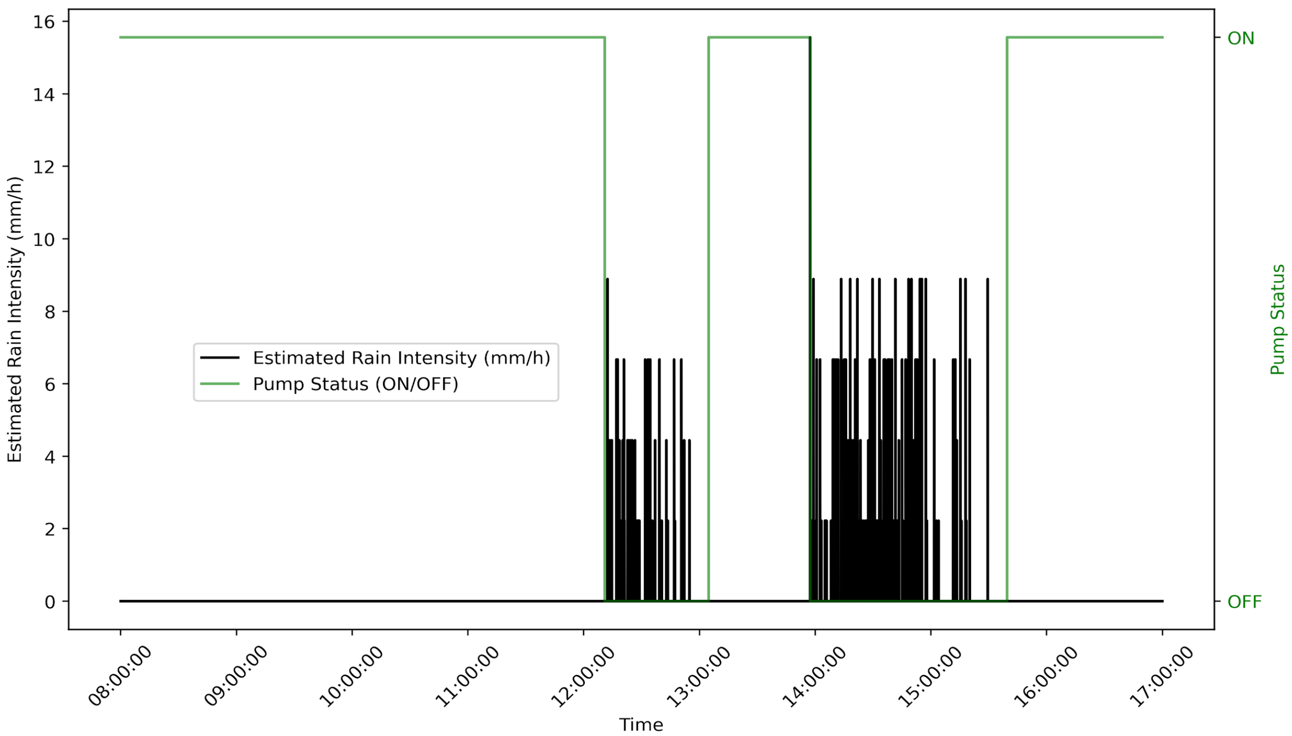

FIGURE 6. Time-series response of pump activation to rainfall sensor input under rain-aware irrigation control

LIGHT INTENSITY AND SOC VS. PUMP STATUS

The system functions in two primary operating modes, namely day mode and night mode, in which battery state of charge (SoC) and ambient light intensity are key factors governing water pump operation. During night mode, when solar generation is unavailable, the pump operates solely using stored battery energy. The SoC (%) reflects the battery's remaining charge, while light intensity measured as an ESP32 analog signal from the LDR sensor indicates the presence or absence of sunlight.

Figure 7 illustrates the relationship between SoC, pump status, and light intensity during the transition from night to early morning. At the onset of morning, light intensity remains insufficient to support photovoltaic power generation, while the daytime control logic has already activated the pump, resulting in a slight initial decrease in SoC. As solar irradiance gradually increases, photovoltaic generation begins to offset the load demand, and the SoC correspondingly stabilizes and then rises. Throughout the nighttime period, the pump operates intermittently under SoC-aware control to maintain root-zone moisture without imposing excessive battery stress. This duty-cycled operation effectively prevents deep discharge while ensuring minimum nutrient circulation. The observed SoC recovery in the morning reflects the system's ability to adapt smoothly to changing irradiance conditions, highlighting the effectiveness of SoC-based energy management for sustaining autonomous hydroponic operation in off-grid tropical environments.

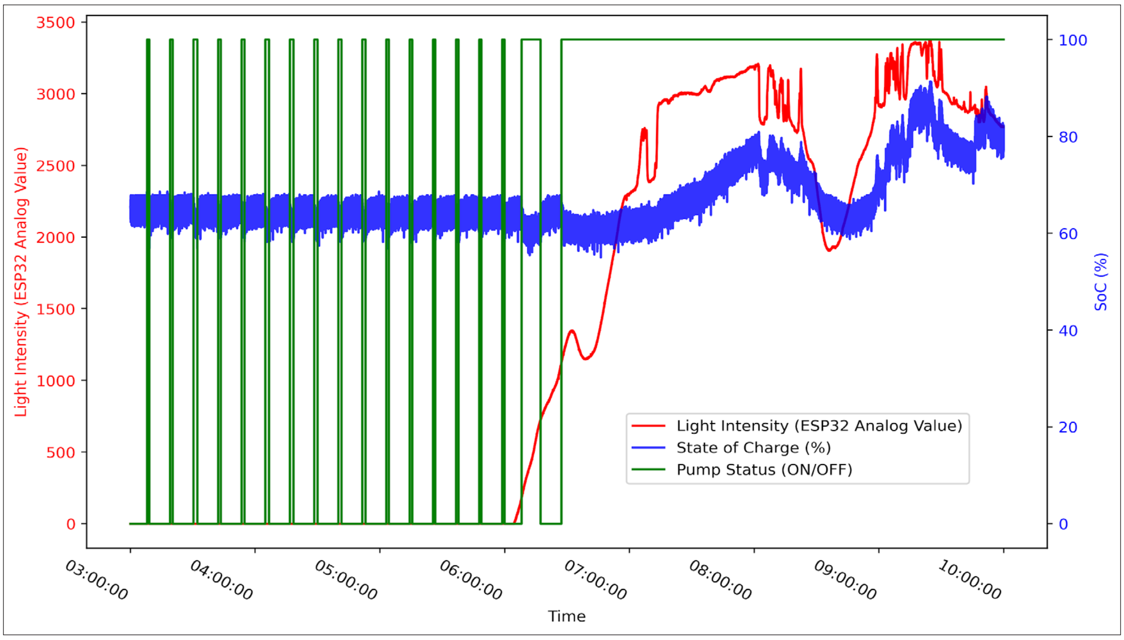

FIGURE 7. Time-series response of SoC, ambient light intensity, and pump status under day–night adaptive energy management

COMBINED VARIABLES VS. PUMP STATUS

Figure 8 presents the relationship between light intensity, SoC levels, rainfall intensity, and pump operation over the course of a day. The graph demonstrates the influence of solar energy availability on battery charging behavior, the impact of rainfall events on pump shutdown, and the resulting SoC variations during charging and discharging cycles.

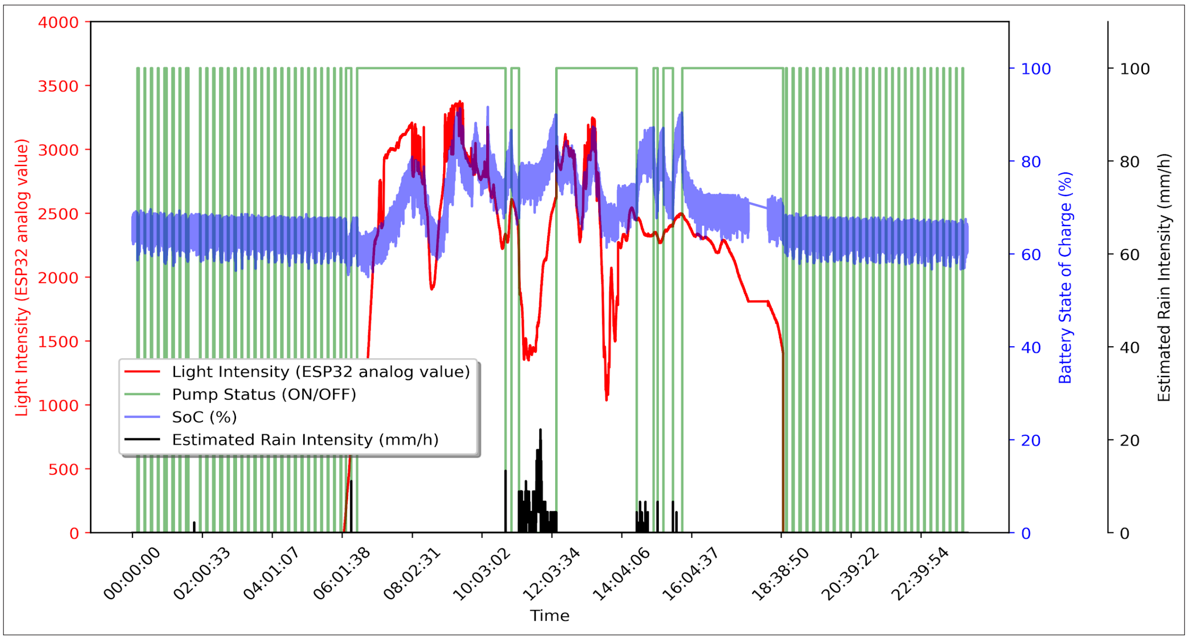

FIGURE 8. Twenty-four-hour system response showing the interaction between environmental conditions, battery SoC, and irrigation pump control

Figure 8 represents the interrelation of various environmental factors with pump status over a 24-hour duration. Light intensity (red line) exhibits a typical diurnal variation; it rises in the morning, peaks at midday, and declines in the evening, affecting the battery charging process. The battery's SoC (blue line) increases steadily during the day because of solar energy input, and after sunset, it starts to decline as energy stored is used. The pump status (green line) remains mainly active during the daytime when there is abundant energy, but rain events (black line), which trigger automatic deactivation, cause intermittent off-cycles. At night, due to voltage drops in the battery, frequent short on-off cycles can be observed where the system shuts down momentarily to maintain energy efficiency, causing the system to restart. The overall trend indicates that the pump is operated dynamically with solar energy, rainfall, and battery charge level detection for energy optimization and continuous operation. The multilayer control reconciles inputs from irradiance, rainfall, and storage conditions, producing coherent supervisory behaviour without manual intervention; observed night cycling indicates conservative protection near the SoC threshold rather than energy scarcity.

DYNAMIC OF SOC LEVEL

Figure 9 illustrates the SoC level changes over four days, sho
pu

activity, and environmental activity. It shows the transitions of charging and discharging cycles, the system's response to detected rain, and the behavior of the pump cycling at night.

SoC or battery charge (measured in percentage) shows above 55% for the entirety of the experiment, and thus energy is available for use. The Exponential Moving Average (EMA) of SoC is observed to oscillate between 60% to 90%. Maximums are recorded during solar charging and pumping and discharging periods, and energy usage results in a gradual decrease. The declination is stalled at nighttime due to frequent pump cycling, which is caused by the voltage sensor reading activating the relay flag. Voltage detection likely causes a repeating relay flag of OFF for 10 minutes and ON for 2 minute every 10 minutes. The voltage detection is likely causing the frame rate to consist of around one update every 10 seconds. It shows the system's automation reaction toward energy balance and sensor-based control logic needing energy management multi-dimensional optimization over the 24-hour cycle distributed across day and night. The multi-day SoC envelope confirms headroom margins during varied weather and validates the smoothing and thresholding strategy; stable autonomy suggests adequate PV-to-load sizing and effective coordination between energy and water subsystems.

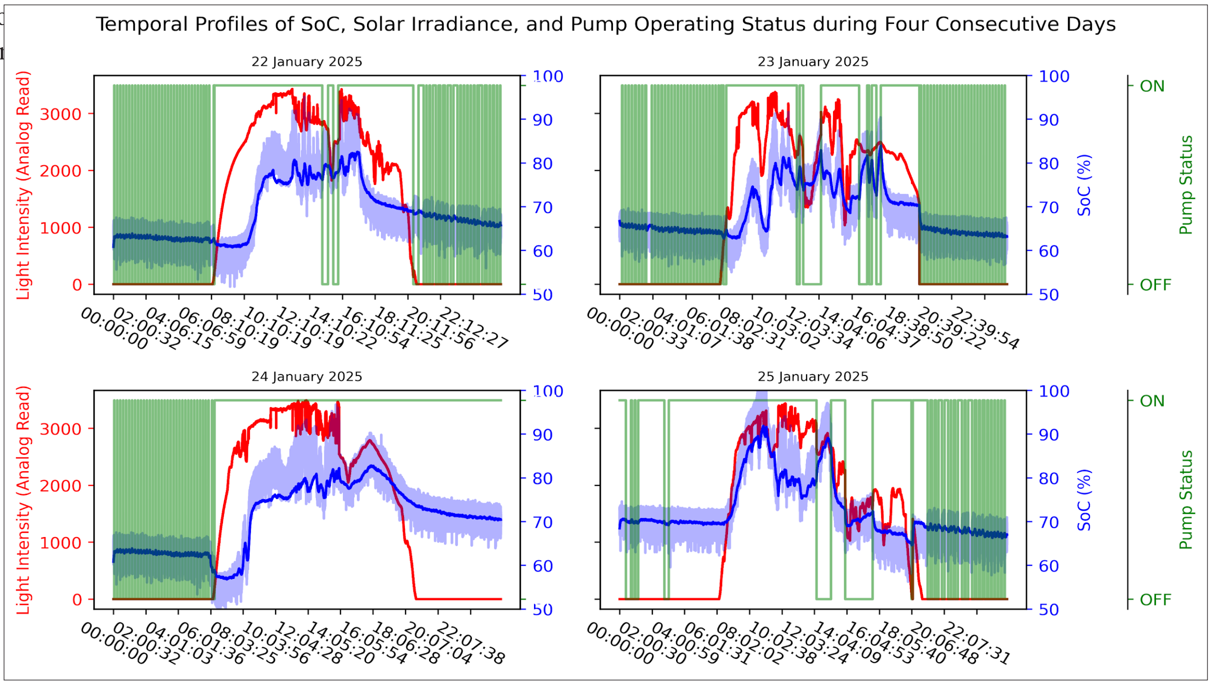

FIGURE 9. Four-day operational response of SoC-aware pump control under tropical outdoor conditions

SOC ESTIMATION ACCURACY

Figure 10 presents the SoC estimation error relative to the EMA-smoothed SoC signal, which was treated as the reference due to its consistency with the calibrated measurement system, evaluated using 5-minute averaged data. The error remains tightly distributed around zero for most operating conditions, indicating stable and consistent SoC tracking under outdoor operation. The achieved MAE of 1.207% and RMSE of 1.689% confirm a high level of estimation accuracy suitable for adaptive energy management. The maximum absolute error of 8.504% occurred sporadically during rapid variations in solar irradiance typical of tropical climates and did not persist over time. Consequently, the resulting SoC accuracy reached 98.79% (MAE-based) and 98.31% (RMSE-based), demonstrating that the adopted voltage–current-based estimation with EMA smoothing provides sufficiently robust performance to support adaptive State-of-Charge control and rain-responsive irrigation in solar-powered multicrop hydroponics systems.

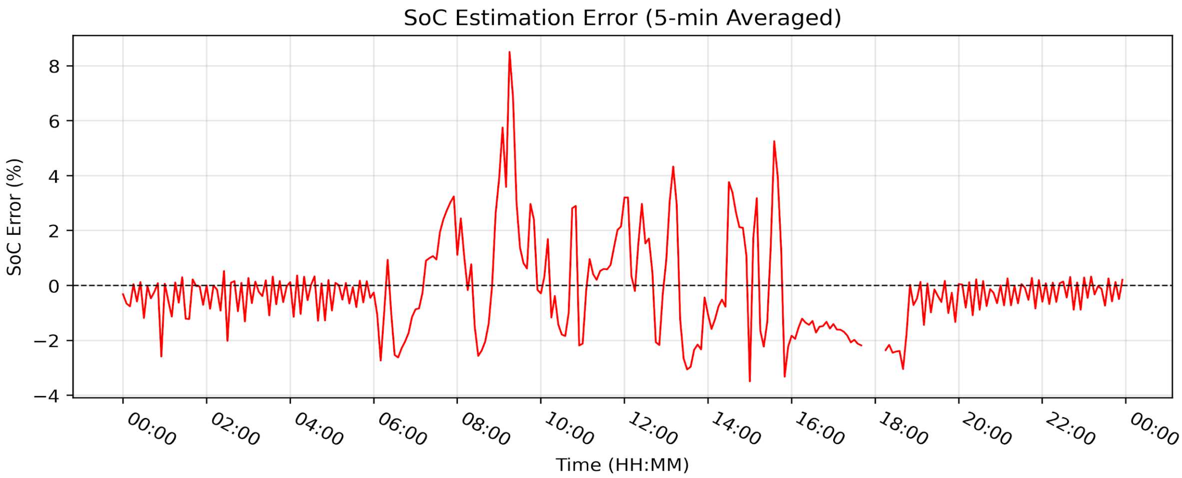

FIGURE 10. Time-series of SoC estimation error referenced to the EMA-smoothed baseline under field operating conditions

SYNTHESIS, LIMITATIONS, AND IMPLICATIONS

Across Figures 3–9, the controller achieved its design targets: SoC remained above a conservative 55% threshold; rainfall-runoff detection curtailed irrigation and preserved nutrient integrity; and night-mode duty cycling avoided deep discharge while maintaining minimum circulation. Mechanistically, coupling SoC-aware scheduling with rain-aware interruption explains the coordinated behaviour observed under tropical variability. The approach aligns with battery-protection guidance (Ruetschi, 2004) and leverages embedded, low-cost sensing consistent with practical constraints in remote agriculture (Demirci et al. 2024; Sorouri et al. 2024; Parajuli et al. 2023; Novaldo et al. 2022; Bakar et al. 2022).

Limitations include reliance on voltage-dominant SoC estimation, which can drift with temperature and dynamic loads; periodic recalibration or adoption of hybrid estimators may improve accuracy (Demirci et al. 2024; Sorouri et al. 2024). Outdoor rain/flow sensors are susceptible to fouling and drift, warranting maintenance schedules and basic self-checks. External validity is bounded by a single site and crop; multi-season, multi-crop, and cross-climate trials would strengthen generalization.

Implications are twofold. Practically, the framework offers a replicable template for off-grid hydroponics on tropical islands, promising lower water consumption, better battery longevity, and reduced maintenance burden. Scientifically, the results substantiate the value of tight energy–water co-control in agri-systems and motivate integration with short-horizon weather forecasts and lightweight hybrid SoC methods, as well as exploration of agronomic outcomes under different crops and nutrient regimes (Gao et al. 2024; Sengupta et al. 2024; Ghiasi et al. 2023).

CONCLUSION

This study has demonstrated that autonomous and reliable operation of an outdoor, solar-powered hydroponic system in tropical island environments can be achieved through the integration of state-of-charge (SoC)–adaptive energy management and rain-responsive irrigation control. The field deployment results confirmed that the proposed control framework successfully maintained battery SoC above a conservative safety threshold under variable irradiance and rainfall conditions, enabling stable energy availability throughout multi-day operation.

The implementation of rainfall-runoff detection effectively reduced unnecessary irrigation during precipitation events, thereby minimizing nutrient dilution and conserving both water and energy. Short, periodic pump activation during rainfall ensured adequate root oxygenation while preventing excessive nutrient loss. During nighttime operation, SoC-aware duty cycling regulated pump activity to avoid deep battery discharge while maintaining minimum nutrient circulation, supporting both battery longevity and plant health.

Time-series analyses of environmental variables, battery SoC, and pump status revealed coherent system responses during day–night transitions and storm events, demonstrating the robustness of the closed-loop supervisory control strategy without the need for manual intervention. Furthermore, the adopted SoC estimation method, based on voltage and power sensing with exponential moving average smoothing, achieved high accuracy under outdoor operating conditions, providing reliable inputs for adaptive energy management using low-cost embedded hardware.

Overall, the principal contribution of this work lies in the development and field validation of a low-cost, integrated control framework that explicitly couples energy availability with irrigation and nutrient management for off-grid hydroponic agriculture. While the present study was limited to a single site and crop configuration, the findings provide a strong foundation for future work, including multi-season and multi-crop validation, integration of short-horizon weather forecasting for anticipatory control, and the incorporation of hybrid SoC estimation and sensor health diagnostics to enhance long-term robustness and scalability.

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DECLARATION OF COMPETING INTEREST

None.

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