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Adaptive Energy Balance Control System via State of Charge (SoC) for a Sustainable Solar-Powered Outdoor-Hydroponics in Tropical Islands

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ABSTRACT: Efficient energy management is essential for sustaining outdoor hydroponics systems powered by solar energy, particularly in tropical island environments where sunlight and rainfall vary throughout the day. To address this, a solar-powered hydroponics system was developed with an adaptive energy balance control strategy based on the State of Charge (SoC). The system requires reliable real-time monitoring and decision-making, achieved by integrating voltage, current (ACS712), light-dependent resistors (LDR), and flow sensors, along with an ESP32 microcontroller for data acquisition and control logic. The adaptive control method dynamically regulates power consumption by adjusting the water pump's operation in response to SoC levels, solar radiation, and rainfall. Experimental validation shows the system maintains the battery's SoC above 55%, ensuring power availability while optimizing energy use. Pump operation is disabled during rainfall and minimized at night to prevent deep discharge, enhancing overall system stability. Daytime solar charging is complemented by controlled discharge during non-solar hours, improving energy sustainability. The results confirm the effectiveness of the proposed strategy in reducing unnecessary energy consumption, improving system reliability, and supporting continuous hydroponic cultivation under varying tropical conditions.

ABSTRAK: Pengurusan tenaga yang cekap amat penting bagi memastikan kelestarian sistem hidroponik luar yang menggunakan tenaga solar, terutama di kawasan pulau tropika yang mempunyai corak cahaya matahari dan perubahan hujan sepanjang hari. Bagi memenuhi keperluan ini, satu sistem hidroponik berkuasa solar telah dibangunkan dengan strategi kawalan imbangan tenaga adaptif berasaskan State of Charge (SoC). Sistem ini memerlukan pemantauan masa nyata dan keupayaan membuat keputusan terpercayai, dicapai melalui integrasi penderia voltan, arus (ACS712), LDR (Rintangan Peka Cahaya), dan aliran, serta mikropengawal ESP32 bagi pemerolehan data dan logik kawalan. Kaedah kawalan adaptif ini mengatur penggunaan tenaga secara dinamik dengan melaras operasi pam air berdasarkan tahap SoC, intensiti cahaya matahari, dan keadaan hujan. Dapatan kajian menunjukkan sistem ini mampu mengekalkan SoC bateri melebihi 55%, sekaligus memastikan bekalan kuasa yang stabil sambil mengoptimum penggunaan tenaga. Operasi pam dihentikan semasa hujan dan dikurangkan pada waktu malam bagi mengelakkan nyahcas bateri berlebihan, seterusnya meningkatkan kestabilan sistem. Pengecasan bateri pada waktu siang dilengkapi dengan penyahcasan terkawal semasa tanpa cahaya matahari, sekaligus memperkukuh kemampanan tenaga. Dapatan kajian membuktikan bahawa strategi kawalan ini berkesan dalam mengurangkan penggunaan tenaga tidak diperlukan, meningkatkan kebolehpercayaan sistem, dan menyokong penanaman hidroponik berterusan dalam persekitaran tropika yang dinamik.

KEYWORDS: *State of Charge, Adaptive Energy Management, Solar-Powered Hydroponics, Power Allocation, Environmental Condition.*

1. INTRODUCTION

The integration of renewable energy into agricultural practices has received considerable attention in recent years. It is essential to have high solar potential, as in tropical islands [1-5]. In Indonesia, where farming remains a major economic activity [6,7,8], solar cell frameworks can sustainably address energy needs [9,10], particularly for solar energy in farming practices such as hydroponics [11,12]. Hydroponics is a method of growing plants without soil, instead using a water solution that contains nutrients [13]. It is most effective in tropical climates that permit year-round farming [14]. Research confirms the effectiveness of hydroponic techniques, reporting significantly higher yields than conventional soil-based agriculture [15-17]. One of the foremost challenges remains the efficient management of energy resources under tropical conditions in solar-powered hydroponic systems [18,19].

The variability of solar irradiance poses a challenge for energy management in solar-powered systems [20,21]. In tropical regions, the variability of solar irradiance is pronounced due to sudden weather changes [22]. These challenges impede the implementation of efficient energy-balance control strategies, increasing the risk that solar-powered hydroponic systems cannot achieve effective energy-supply control for consistent plant growth. Management of energy within the system is also critical because overcharging and over-discharging lead to excessive battery cycling, damage to essential components, and reduced overall system efficiency [23-25]. Real-time consideration of the link between energy supply and demand is necessary for energy management systems to address these problems [26-28]. One of the most effective methods is State-of-Charge (SoC)-based adaptive energy balance control [29,30]. SoC, a critical determinant of energy flow in hydroponic systems, denotes the state of charge of energy storage systems such as batteries [31]. With real-time SoC measurement, adaptive control can adjust energy expenditure based on the current state of stored energy [32]. This method not only permits the trimetallic components to function optimally but also ensures the continued operation of essential functions, such as water nutrient pumping. This paper builds on existing SoC-based control strategies by introducing a novel integration of rainwater runoff detection and management to further optimize water and energy use in solar-powered hydroponic systems designed for tropical island environments. The integration of SoC-based energy management with dynamic water-use adjustments in response to rainfall events represents a significant advancement in sustainable hydroponic practices.

Although several studies have implemented solar-powered hydroponics and SoC-based energy management [29–32], most do not integrate adaptive control with rainfall detection for water-energy optimization in tropical outdoor conditions. Furthermore, existing frameworks often lack practical validation in off-grid island environments, where high solar intermittency and rainfall variability pose unique challenges. This study addresses these gaps by developing and experimentally validating a novel SoC-adaptive energy balance control system that incorporates rainwater management, thereby ensuring continuous hydroponic cultivation under tropical variability.

This paper aims to achieve the following: (1) create an SoC-based adaptive control of energy balance for a solar-powered outdoor hydroponics system tailored for tropical islands and (2) evaluate how effective the system is in optimizing energy consumption and reliability in tropical conditions. This control strategy enables appropriate adaptive responses to changes in energy availability and requirements, thereby reducing inefficiencies and the risk. This study focuses on improving sustainable agriculture policies in tropical regions.

2. METHOD

This study employs an SoC-based approach to design and evaluate an adaptive energy-balance control system for a sustainable solar-powered hydroponic system in a tropical environment. The methodology includes three main steps: system design and algorithmic strategy formulation, prototype implementation, and system dependability assessment.

2.1. Solar-Powered Outdoor Hydroponics System

The system is engineered to incorporate solar photovoltaic, energy storage, and hydroponic subsystems, with adaptive energy-balance management. The design is illustrated in the system block diagram in Figure 1, which depicts the interactions among the solar PV panels, battery storage, hydroponic subsystems, and energy management components.

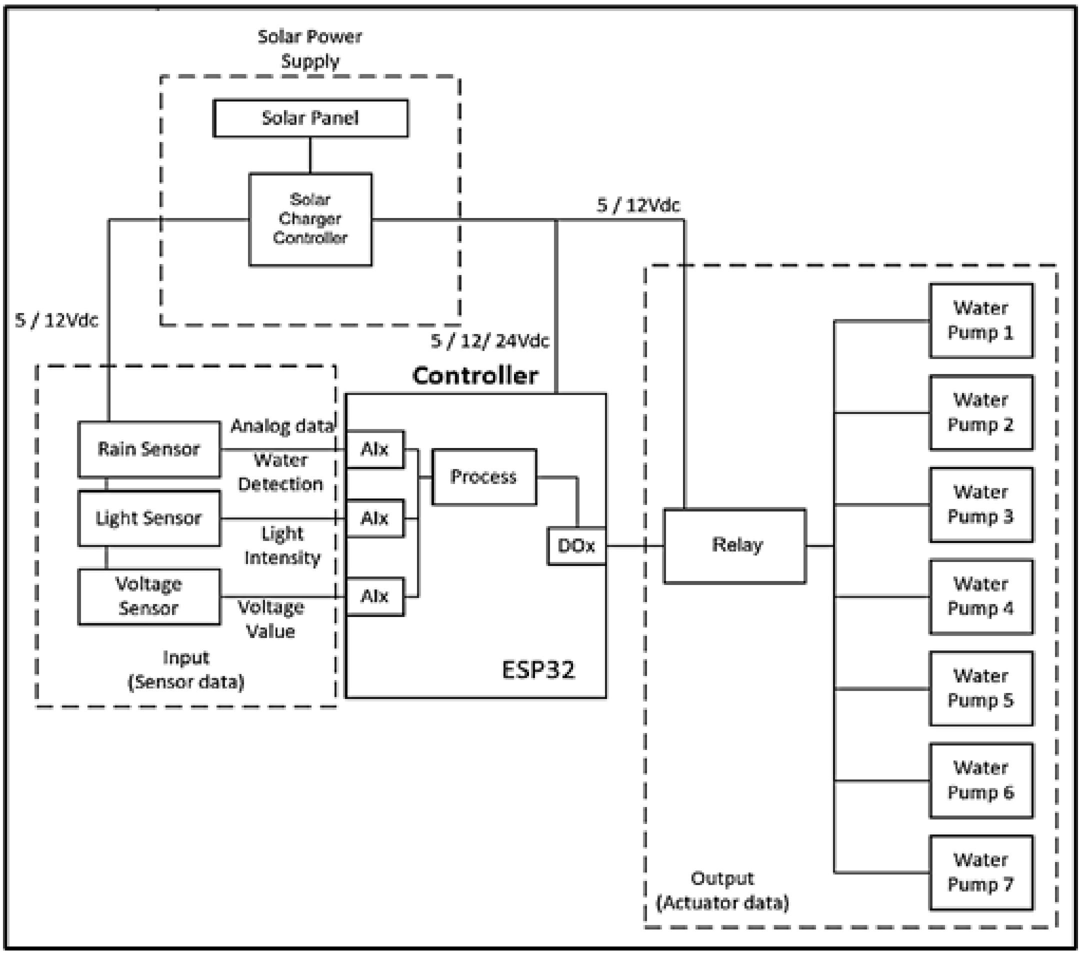

Figure 1. System Block Diagram

2.2. SoC-Adaptive Control System

The adaptive energy balance control algorithm, based on SoC, governs the reservoir's pumping activities by allocating pumping energy based on real-time SoC measurements and available energy. The SoC status is calculated inside the microcontroller using the following simple approach:

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

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 [33].

Fluctuations in charging and discharging cycles will not yield an accurate SoC value. Voltage-based estimation provides an effective means of battery protection, as it disables power-pumping commands when the SoC is reported below 55%. The 55% SoC threshold was chosen to provide a protective margin for the lead-acid battery, thereby reducing degradation risk. Literature confirms that operating below 50% SoC accelerates sulfation and reduces lifespan [24,25]. By selecting 55%, the system balances usable capacity with long-term reliability, ensuring uninterrupted hydroponic operation. Operating below this threshold for extended periods can lead to increased battery degradation and shorten its lifespan [34]. Furthermore, maintaining a buffer above 55% enables the system to handle unexpected increases in energy demand or prolonged periods of low solar irradiance, ensuring the continuous operation of critical functions such as nutrient pumping. SoC determination using characteristic parameters is performed during the investigation, as it is based on the Open Circuit Voltage and internal resistances, as modified [35,36].

The system automatically controls the pump's operation, causing it to turn on and off at scheduled intervals. Meanwhile, the solar panels generate electricity. Consequently, the voltage level changes over time. The value of its fluctuation is determined by the internal resistance of the battery system, which can be defined as:

$$R_{int} = \frac{V_{no\ load} - V_{load}}{I_{load}} \tag{2}$$

R_{int} is to be measured in ohms (Ω) and defined by the value of the voltage drop concerning the 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 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 between the no-load and loaded voltages divided by the current drawn [37]. It is one of the factors used to smooth the voltage value for analysis. The smoothed voltage estimate is used to calculate SoC for analysis.

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

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

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

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:

$$\alpha = \frac{2}{N+1} \tag{5}$$

where N represents the selected window size or period for smoothing [38]. The EMA helps reduce fluctuations in voltage measurements, providing a more stable representation of SoC dynamics over time.

The adaptive approach relying on SoC guarantees the retention of optimal energy usage without exceeding the battery discharge limit. The algorithm operates by first collecting real-time SoC data, solar energy data, and the hydroponic system's energy needs. It allocates energy based on system demands, ensuring that critical functions remain operational even during periods of low energy supply. For greater efficiency, a rain sensor is installed to automatically control water pumping, reducing excess irrigation and water waste during rainfall. In addition, the algorithm adjusts the supplied power to different subsystems to optimally balance demand and supply, thereby extending the battery's operating time. The algorithm's logic and feedback control structure are shown in a flowchart in Figure 2.

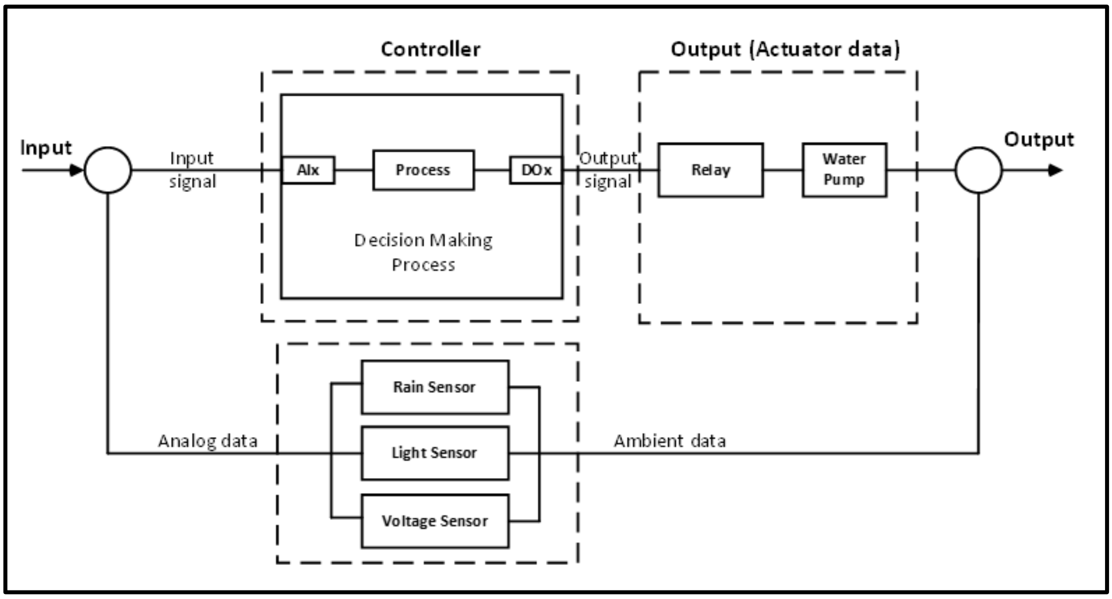

Figure 2. Decision-Making Process and Feedback Control Loops

The flowchart depicts an automated hydroponics water-pumping system with an adaptive decision-feedback control structure. The process starts with setting digital pins for relay control and defining essential variables, which are rain detection, light, and battery SoC. Moreover, the system continuously monitors a rain sensor, LDR (light-dependent resistor), and a voltage sensor to capture environmental and battery data. The first check is to determine whether it is raining; if rain is detected, all water pumps will be switched off to avoid unnecessary irrigation and conserve water resources. If no rain is detected, then the system checks if there is daylight. If yes, all water pumps will be turned on to facilitate irrigation. If there is no daylight, the system checks the battery's SoC. If the SoC drops below 55%, pumps are set to an energy-saving mode where they run for two minutes and then pause for ten minutes to conserve battery. This feedback control loop adapts in real time to changes in environmental conditions to maximize battery and water use in an energy-efficient manner. Adaptive energy management enables the system to conserve battery power, while rain detection reduces water usage, optimizing the system for sustainable, autonomous, and scalable hydroponic solutions.

The novelty of this method lies in its integration of SoC-adaptive control with rainfall detection, enabling dynamic pump regulation that conserves both energy and water. Unlike conventional SoC-based approaches [33–36], our system introduces a multi-criteria feedback loop (SoC, solar irradiance, and rainfall) to ensure stable operation in tropical outdoor conditions. This combined strategy provides resilience against both energy intermittency and nutrient dilution risks, which are rarely addressed simultaneously in previous studies.

2.3. Rain Protection System

The rain protection system is designed to efficiently manage drainage to prevent excess water from disrupting the equilibrium of the outdoor hydroponics system. The system's main components are an automatic valve that controls water entering the nutrient bucket, a water-collection mechanism, and a rainwater runoff detection system.

2.3.1. Rainwater Runoff Detection

Rainwater can significantly affect the nutrient solution concentration in an outdoor hydroponics system; therefore, the system uses a flow sensor to detect the presence and volume of runoff. A water collector is installed to collect rainwater runoff from the surface of the solar panels, thereby ensuring accurate detection. The two main purposes of this arrangement are to ensure that the collected water volume is sufficient for the flow sensor to detect accurately and to provide an early warning of excess rainfall runoff that might enter the hydroponics system.

The rationale for collecting runoff from solar panels is that the onset of water flow from the panels indicates that precipitation is accumulating and may soon enter the hydroponic system. Early detection enables the system to act promptly to control water flow and prevent undesired dilution of the nutrient solution, thereby preserving optimal growing conditions for the plants.

2.3.2. Excess Water Control

A backflow prevention device is equipped with a nutrient backflow pipe that contains a drain hole to reduce the concentration of diluted nutrient solution resulting from rainfall intake. Excess rainwater can be discarded before it reaches the nutrient bucket. Thus, unwanted water is prevented from contaminating the nutrient solution. If the flow sensor detects additional runoff, all pumps are automatically shut off, allowing the remaining nutrient solution to drain from the hydroponic pipes back to the nutrient bucket. This system averts overfilling while preserving the hydroponic nutrient solution’s concentration required for optimal plant growth.

Mechanically, a ball-type automatic valve is used to regulate the flow of water into the nutrient bucket, in addition to the drain hole. Under system-optimal conditions, the valve remains open until the volume of collected rainwater exceeds a specified threshold. Consequently, below the designated threshold, the hydroponic system can operate as designed. If collected rainwater exceeds a predetermined threshold, the floating ball mechanism will guide the valve to close, preventing further entry of non-nutrient water for plant nourishment. It facilitates the minimization of water-solution imbalance despite heavy rainfall.

2.4. 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 with a capacity of 12V and 160 Wp, providing an uninterrupted power supply. A 12V 200Ah lead-acid battery bank handles energy storage and dispatching. The system employed two 12V DC submersible water pumps (flow rate 1.2 L/min, head 2.0 m, power consumption 15 W each). These were selected for their low power demand, corrosion resistance, and suitability for continuous NFT hydroponic circulation. The energy monitoring sensors enhance resource optimization. For autonomous control, sensors measuring SoC, solar irradiation, and rainwater runoff are processed by an ESP32 microcontroller executing an SoC-based control algorithm. The system was installed in the tropical outdoor environment in Lenek District, East Lombok, West Nusa Tenggara, a region characterized by a tropical climate with distinct wet and dry seasons. The prototype was operated and monitored continuously for four days, from May 15–18 May 2025, coinciding with the transition into the dry season. This period was intentionally selected because it experiences high daytime irradiance with intermittent afternoon rainfall, providing a suitable test of the system's ability to maintain SoC stability under variable tropical weather conditions. The hydroponic system employed was a Nutrient Film Technique (NFT) system, consisting of two parallel channels for cultivating lettuce (Lactuca sativa L.). This setup enabled the evaluation of the system's energy management efficiency, responsiveness to changes in solar irradiance, and performance under adverse weather conditions. As summarized in Table 1, the proposed SoC-adaptive hydroponics control demonstrates clear improvements over previous studies by integrating rainfall awareness and energy optimization, thereby maintaining system reliability with SoC levels consistently above 55%.

Alternative approaches, such as timer-based control Novaldo *et al.,* 2022 [10] or simple automatic irrigation strategies Chaiwongsai, 2019 [14] have been proposed but lack adaptability to fluctuating energy and weather conditions. Similarly, aquaponics prototypes using Arduino [12] demonstrated monitoring capability but lacked active SoC-based optimization. In contrast, our approach not only maintains an SoC above 55% but also adapts irrigation in response to rainfall, offering a more sustainable and robust solution for tropical environments.

Table 1. Comparison of the Proposed SoC-Adaptive Hydroponics Control with Previous Studies

Study	Application Context	Control Approach	Key Features	Reported Limitations	Performance Outcome
Novaldo et al., [10]	Pilot hydroponics, Indonesia	Solar-PV + timers	Simple automation	No adaptive SoC; not rainfall aware	Stable only in dry conditions
Bakar et al., [12]	Aquaponics prototype	Arduino + SMS alert	Remote monitoring	No energy optimization	Limited system reliability
Chaiwongsai [14]	Tropical hydroponics	Automatic control	Focus on growth environment	Lacked integrated energy control	High water use
This study	Outdoor hydroponics, tropical island	SoC-adaptive + rainfall integration	Energy-efficient, rainfall adaptive	Requires calibration	Maintained SoC > 55%, improved reliability

3. RESULTS AND DISCUSSION

The SoC-based adaptive energy balance control was created for an efficient solar-powered outdoor hydroponics system tailored for tropical islands.

3.1. System Implementation

3.1.1. Excess Water Control

Figure 3 depicts a collection and management system designed to efficiently regulate water. It consists of a storage container with a float valve, an excess water outlet, and an emergency cleaning drain. The float valve (indicated in red) controls the water level, preventing overflow while preventing waterless cleanup due to excessive rain inflow. Overflow water (excess water) from the piping maintains equilibrium, preventing the storage container from exceeding its capacity. An emergency or cleanout valve is integrated into the system to enable maintenance and cleaning of the drainage system when required to maintain controlled drainage. The entire assembly is constructed from PVC pipes, which makes it durable and easy to install in a wide range of environmental conditions.

Figure 3. Backflow pipe for nutrient circulation with excess-water control, using a floating ball valve for regulation.

3.1.2. Sensors and Microcontroller ESP32

Figure 4 shows a smart sensor-based control system for a solar-powered outdoor hydroponics system that manages energy and water flow based on the State of Charge (SoC) level. The system employs an ESP32 microcontroller (cyan) as the primary processing unit, controlling system operations via the sensors.

The rainwater harvesting system (blue) temporarily stores rainwater from the solar panels. As the water level in the temporary collection chamber reaches a predefined threshold, it signals potential rainwater inflow into the hydroponic system. The flow sensor (blue) detects water movement and signals the ESP32 to turn off the relay module (red), preventing nutrient solution dilution.

An orange Light Dependent Resistor (LDR) is used to identify whether the system operates in day or nighttime mode. The system's on/off control cycle operates based on the state of charge (SoC), which is typically determined by a voltage sensor (green) within the system. However, because voltage readings alone do not provide sufficient information for accurate SoC estimation, a real-time current sensor such as the ACS712 (magenta) is used to improve SoC estimation accuracy.

Figure 4. Sensor Integration for SoC-Based Adaptive Energy Balance Control in a Solar-Powered Outdoor Hydroponics System.

The adaptive control system with integrated sensors actively manages energy use and nutrient balance to achieve greater efficiency, advancing the goal of a self-sustaining, solar-enabled hydroponic farming system. The implementation of this control mechanism is illustrated in Figure 5.

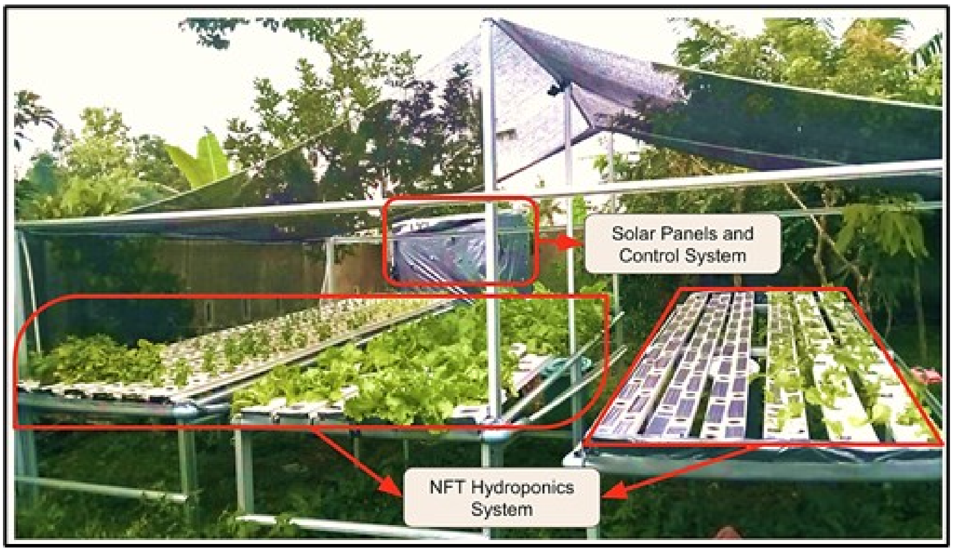

Figure 5. Implementation of Solar-Powered NFT Hydroponics System with Integrated Control Mechanism.

It depicts a hydroponic system employing the NFT technique, controlled by a solar system. The system comprises two parallel NFT hydroponic channels in which crops are grown under a constant flow of nutrient solution. The solar panels, along with the control unit, are mounted above the hydroponic system to enable autonomous operation using renewable energy.

The solar panels have a dual purpose: in addition to providing electricity to the hydroponics system, they also serve as a surface for collecting rainwater. The collected rainwater is stored in monitoring vessels before being processed by the system's adaptive energy balance control. Nutrient dosing, relay switching, and various growth-condition sensors are controlled by the system's ESP32 microcontroller, which also measures environmental parameters to ensure optimal growing conditions.

As summarized in Table 2, integrating voltage, current, light, and rain sensors with the ESP32 microcontroller enables accurate monitoring, efficient energy use, and reliable automation. This consolidated sensor suite enables the system to maintain optimal SoC estimation, regulate nutrient balance, and achieve self-sustaining operation.

Table 2. Sensors used in the SoC-Adaptive Hydroponic System

Sensor	Type	Specification	Accuracy	Function
Voltage Sensor	ZMPT101B	0–25 V input	±0.5%	Battery voltage monitoring
Current Sensor	ACS712	0–30 A	±1.5% FS	Current measurement for SoC
Light Sensor	LDR	10–1000 lux	±5%	Day/night detection
Rain Sensor	YL-83 + flow sensor	0–5 mm/min sensitivity	±2%	Rainfall detection
Microcontroller	ESP32	Dual-core, WiFi/BT	–	Data processing & control

3.2. Rain Detection vs. Pump Status

Proper management of water resources is vital in hydroponics and irrigation systems to prevent oversaturation and optimize resource efficiency. The system incorporates a rain-detection feature that uses a flow sensor to detect rainwater runoff, thereby helping to control the operation of the water pump. During day mode (08:00 – 16:00), the pump operates on a modified thermal strategy. It is shut off for 10 minutes whenever runoff is triggered, then turned back on for 2 minutes before re-evaluating runoff detection. This cyclical strategy ensures that plants are adequately nourished while minimizing excess water use during periods of rainfall. Figure 6 shows the relationship between rain intensity and pump status, illustrating the system's behavior in response to environmental conditions in real time.

The graph depicts the correlation between rain intensity (mm/h) and pump activity (ON/OFF) during semi-automated daytime operations (LDR reads light), in which pump operation is controlled by a flow sensor that detects rainwater runoff. The blue line illustrates the rainfall intensity, while the red 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 as rainfall runoff continues to be detected, thereby avoiding unnecessary irrigation during rainfall. As shown in the graph, during the period of significant rainfall, which occurs between approximately 11:00 AM and 12:30 PM, the pump is detected to be OFF most of the time due to abundant runoff. In the absence of rainwater runoff for over 10 minutes, however, the system then resumes normal operations for nutrient augmentation. For daytime operation, the pump behaviour ignores SoC and aims solely to use water efficiently, with operation controlled by rainfall. It helps prevent over-irrigation while ensuring that nutrient levels remain adequate during periods of rainfall cessation, thereby sustaining efficient water management.

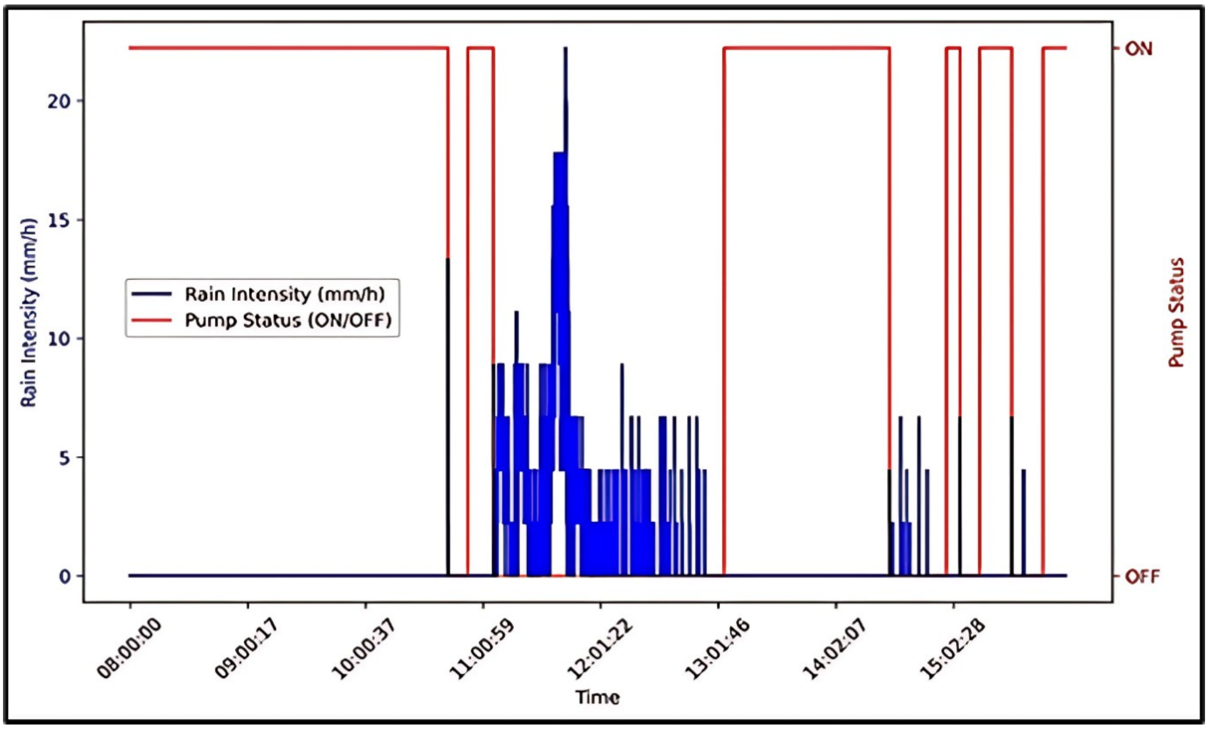

Figure 6. Rain sensor signal vs. pump status during daytime operation (16 May 2025).

3.3. Light Intensity and SoC vs. Pump Status

The system operates in two distinct modes: day and night, in which the battery State of Charge (SoC) and light intensity are critical determinants of water pump operation. During night mode, when solar energy is unavailable, the pump relies entirely on battery power. The SoC (%) represents the battery state of charge, while the light intensity (analog read) indicates the presence or absence of sunlight.

The graph in Figure 7 illustrates the relationship between SoC, pump status, and light intensity during the transition from day to night. As shown in the graph, light intensity declines significantly after sunset, resulting in a gradual decrease in SoC as the battery discharges. The water pump operates intermittently according to predefined control logic to prevent excessive battery discharge. When the SoC reaches a critical threshold, the system may regulate pump activity to conserve energy. This analysis highlights the importance of energy-efficient water management in off-grid hydroponic or irrigation systems.

The graph depicts the relationships among SoC, pump status, and light intensity over time, particularly during the transition from day to night. The light intensity (orange line) drops significantly after sunset, indicating the absence of solar energy. As a result, the system switches to battery power, causing the SoC (green line) to decrease as energy is consumed gradually. The pump status (red line) shows periodic operation, indicating that the pump is intermittently controlled to prevent excessive battery discharge. Initially, when the battery is fully charged, the pump operates more frequently. However, as the SoC declines, the system regulates the pump's operation, likely to conserve energy for critical functions. The fluctuations in SoC suggest minor variations in power consumption and battery efficiency throughout the period. It highlights the importance of energy management in off-grid systems, ensuring that the water pump operates while maintaining sufficient battery levels for nighttime use.

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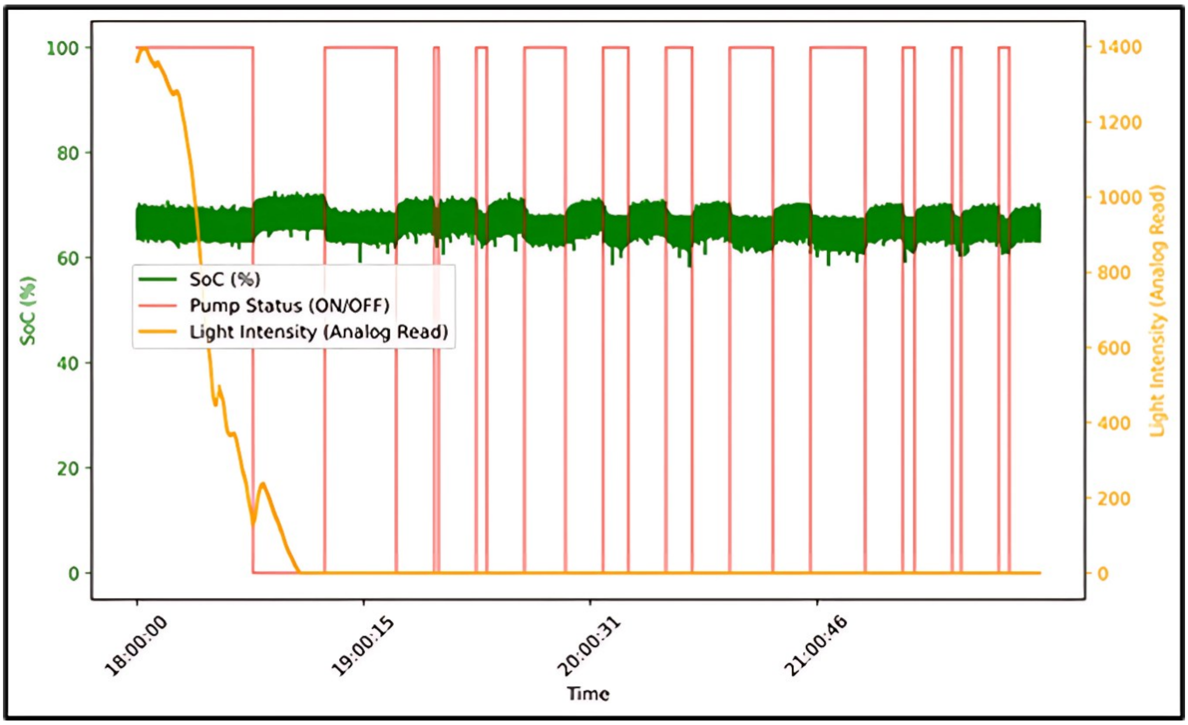

Figure 7. SoC vs. pump status during nighttime operation (16 May 2025).

This analysis highlights the importance of energy-efficient water management in off-grid hydroponic systems. Compared with conventional SoC-based systems that only regulate pump activity based on battery charge [19,20], our system integrates SoC with real-time light intensity and rainfall conditions, providing multi-criteria control. This approach ensures stable operation at night while conserving battery resources, a feature not reported in timer-based or single-parameter control systems [10].

3.4 Combined Variables vs. Pump Status

The graph in Figure 8 illustrates the correlation among light intensity, SoC levels, rainfall intensity, and pump activity throughout the day. It highlights the impact of solar energy availability on battery charging, the effect of rainfall on pump deactivation, and the fluctuations in SoC during charging and discharging cycles.

This graph depicts the relationships between various environmental factors and pump status over 24 hours. Light intensity (orange 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 (green line) increases steadily during the day due to solar energy input, and after sunset, it begins to decline as stored energy is used. The pump status (red bars) remains predominantly active during the daytime, when energy is abundant, but rain events (blue bars), which trigger automatic deactivation, cause intermittent off-cycles. At night, due to voltage drops in the battery, frequent 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 operates dynamically, using solar energy, rainfall, and battery charge-level detection to optimize energy use and ensure continuous operation.

The overall trend indicates that the pump operates dynamically in response to solar irradiance, rainfall, and battery state of charge. This contrasts with earlier hydroponic energy management strategies that primarily relied on solar availability or pre-set schedules without SoC thresholds [10,12]. By integrating rainfall detection, our system prevented unnecessary

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irrigation during wet conditions, thereby improving water efficiency and ensuring uninterrupted hydroponic operation even during periods of environmental variability.

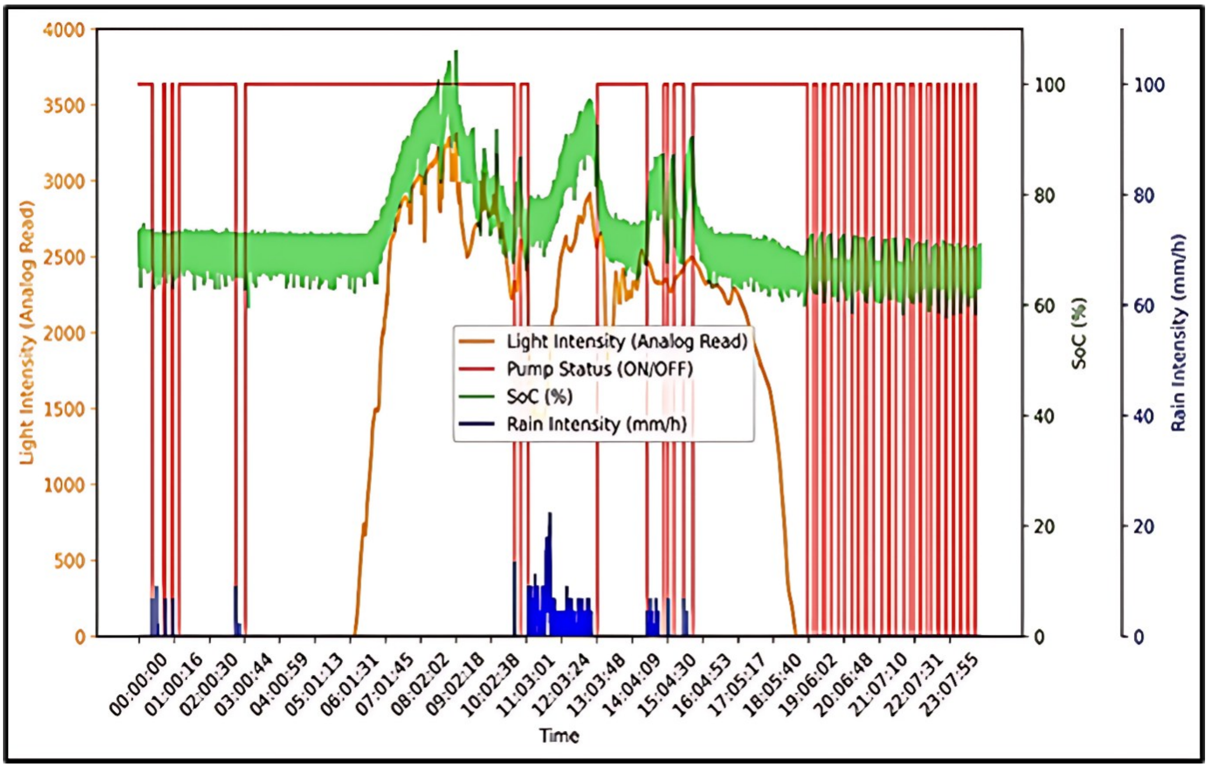

Figure 8. System dynamics under combined variables (rainfall, light intensity, and SoC level) affecting pump status over a 24-hour cycle (17 May 2025).

3.5 Dynamic of SoC Level

Figure 9 illustrates the SoC-level changes over four days, showing correlations with battery charge, pump activity, and environmental activity. It shows the transitions between charging and discharging cycles, the system's response to detected rain, and the pump's cycling behavior at night.

SoC or battery charge (measured as a percentage) remains above 55% throughout the experiment, indicating that energy is available for use. The Exponential Moving Average (EMA) of SoC oscillates between 60% and 90%. Maximums are recorded during solar charging,pumping, and discharging periods, and energy usage gradually decreases. Declination is halted at night due to frequent pump cycling, triggered by the voltage sensor reading that activates the relay flag. Voltage detection likely causes a relay flag to alternate between OFF for 10 minutes and ON for 1 minute every 10 minutes. Voltage detection is likely causing the frame rate to be approximately one update every 10 seconds. It shows the system’s automated response to energy balance and sensor-based control logic, requiring multidimensional energy management optimization over the 24-hour cycle, distributed across day and night.

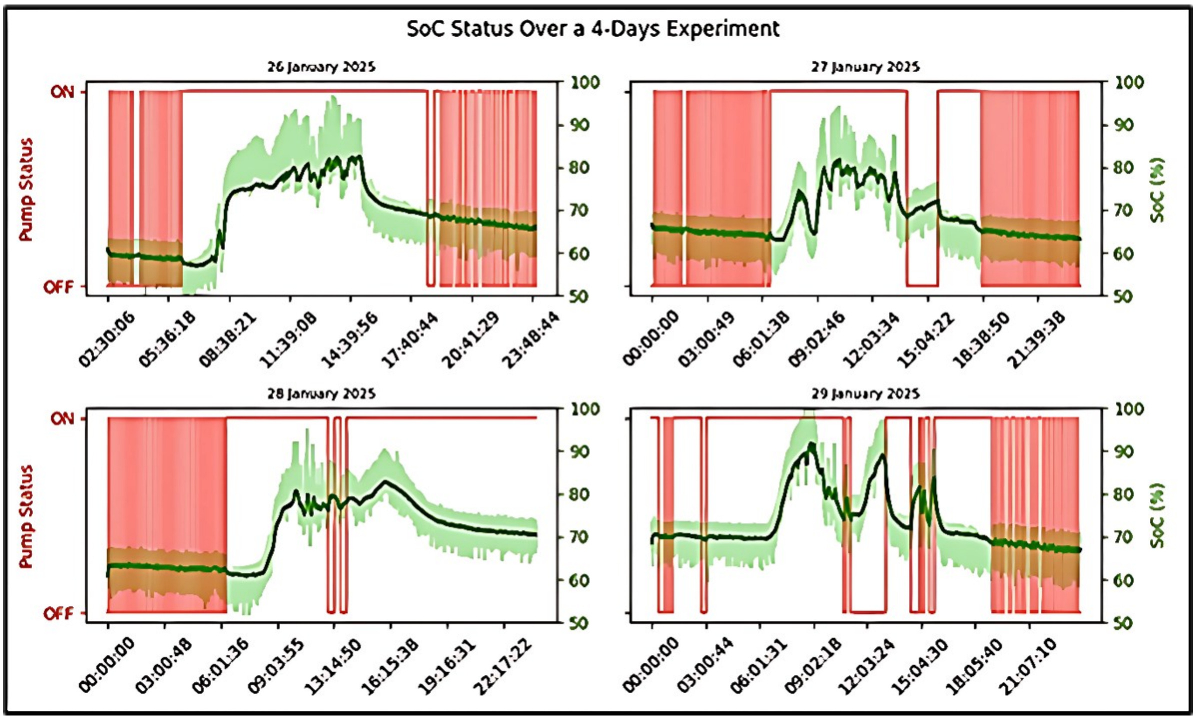

Figure 9. SoC variation over four days (15–18 May 2025).

4. CONCLUSION

This study demonstrated the effectiveness of a SoC-based adaptive control strategy for solar-powered outdoor hydroponics in tropical island environments. The system consistently maintained SoC above 55%, thereby ensuring a continuous energy supply for irrigation while preventing deep discharge. Pump operation was dynamically adjusted, turned off during rainfall, and cycled at night to conserve both water and energy. Compared with previous hydroponic energy management frameworks that relied solely on timers or solar availability, our system integrated rainfall detection and multi-criteria control, resulting in higher system resilience and sustainability. The findings align with recent reports on greenhouse and aquaponic energy management but extend their applicability to real-world tropical conditions. This demonstrates that adaptive SoC-rainfall integration can significantly improve reliability and resource efficiency, contributing to sustainable agriculture in off-grid environments.

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