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IoT-Based Smart Light Control System for Shading Optimization in Agrivoltaic Systems

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***Abstract*—Agrivoltaic systems (AVS) integrate agriculture with photovoltaic (PV) systems on the same land which allowing dual use for both crop production and electricity generation. However, poorly managed shading from PV structures can negatively impact crop growth. This paper presents an IoT-based smart light control system designed to optimize shading through dual-axis solar panel adjustment using real-time environmental data. The proposed system employs an ESP32 microcontroller as the main controller unit and utilizes a dual-axis solar tracking mechanism driven by two servo motors. Light-dependent resistor (LDR) sensors are used to detect light intensity and direction, while a soil moisture sensor continuously monitors soil water content and automatically activates an irrigation pump when moisture levels fall below a predefined threshold. Visual and audible indicators, including an LCD display, LEDs, and a buzzer, provide real-time feedback on system status, soil conditions, and environmental responses. An IoT platform based on the Blynk application enables real-time data visualization, remote monitoring, and manual control of the irrigation system via a mobile interface. By integrating adaptive shading control with automated irrigation, the system provides a more efficient and sustainable solution for managing solar exposure and soil moisture compared with traditional fixed PV structures and manual agricultural practices.**

***Index Terms*—Agrivoltaics, Internet of Things (IoT), Solar Tracking, Smart Irrigation.**

I. INTRODUCTION

The global demand for renewable energy and sustainable agricultural practices continues to increase due to rising energy consumption, limited land availability, and the growing effects of climate change. Agrivoltaic systems (AVS) have emerged as an innovative solution by integrating solar energy generation with agricultural activities on the same land area [1][2]. This approach allows crops to be grown while simultaneously producing clean and renewable electricity, thereby maximizing land-use efficiency. With increasing energy costs and shrinking agricultural spaces, AVS are increasingly recognized as a practical method to support food security and sustainable energy production. As a result, agrivoltaics (AV) has gained attention worldwide as a promising approach to address energy and agricultural challenges in a single integrated system [3].

Despite these advantages, the challenges in AVS are maintaining an optimal balance between solar energy harvesting and crop growth [4][5]. PV panels inherently cast shadows that can significantly alter the microclimate beneath them, affecting light availability, soil moisture, and crop growth. While partial shading can be beneficial for certain crops by reducing heat stress and evapotranspiration, excessive or poorly distributed shading may lead to reduced photosynthesis and lower yields [6][7]. Conventional AV installations typically rely on fixed PV panel configurations or manual adjustments, which lack the flexibility required to respond to dynamic environmental conditions such as changing sunlight intensity, seasonal variations, and crop-specific light requirements.

Recent advancements in the Internet of Things (IoT) have enabled intelligent monitoring and control systems capable of real-time environmental sensing. IoT-based solutions have been widely applied in precision agriculture to improve irrigation efficiency, climate control, and resource management. Similarly, smart PV tracking systems have been developed to enhance energy harvesting by adjusting panel orientation based on solar position. However, the integration of IoT-enabled solar tracking with crop-oriented shading optimization and automated irrigation in AVS remains limited.

To overcome these limitations, an IoT-based smart light control system (SLCS) for shading optimization in AVS is proposed to support both efficient energy production and sustainable agricultural practices. The primary objectives of this study are to design and develop an automated dual-axis PV tracking system that optimizes sunlight exposure for both solar energy generation and crop growth in AV environments and enable remote monitoring and control through an IoT platform.

II. RELATED STUDIES OF SMART LIGHT CONTROL FOR AGRIVOLTAICS

The advance of artificial lighting systems in order to improve insufficient natural sunlight in greenhouse environments has been explored by [8]. In the research, LED-based artificial lighting has been proposed to improve plant growth during low solar radiation. An STM32 microcontroller integrated with light sensors is used to monitor illumination levels, while data are transmitted to the ThingSpeak platform for real-time

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monitoring and control. The primary objective of the system is to improve crop quality and enhance energy efficiency through precise light-level regulation. However, reliance on artificial lighting increases system cost and energy consumption, thus potentially limiting scalability for large-scale agricultural applications.

Other research by [9] proposed a project Enhancing Land Use: Integrating Bifacial PV and Olive Trees which investigates compatibility of solar panels of bifacial type and olive trees planting. Field testing in a Mediterranean environment quantifies the plant productivity and plant energy output. The panels to enhance efficiency gather both left and right sunlight. The findings, nevertheless, can be applied only to one type of crop and setting. The proposed system is more flexible, given that adjustment to specific crops and weather conditions can be done, changing the panel position to reflect the sunlight in real-time without expensive deployments of bifacial panels.

The performance of V-shaped bifacial solar panels in an agricultural context has been investigated by [10] through a simulation-based. The study evaluates the energy efficiency and shading characteristics of V-shaped bifacial photovoltaic systems in comparison with conventional flat-panel configurations. By utilizing solar geometry analysis and crop growth modelling, the research provides valuable insights into the potential energy gains and shading patterns achievable through advanced panel designs. However, the study primarily relies on theoretical simulations and does not address practical challenges such as construction complexity, system cost, and real-world deployment constraints.

In addition, [11] analysed the electrical performance of a single-axis solar tracking system to evaluate seasonal energy yield improvements. Their work demonstrated that dynamic tracking significantly increases power output compared to fixed solar panels by maintaining optimal alignment with the sun throughout the day. While the study effectively highlights the benefits of solar tracking for energy generation, it does not consider agricultural requirements such as crop shading or irrigation control.

Furthermore, a simulation-based investigation by [12] on agricultural-friendly single-axis dynamic AV assessed the impact of movable photovoltaic panels on both energy production and agricultural income. The study compared fixed and dynamic PV systems using meteorological data and demonstrated improved performance with dynamic tracking. However, the lack of physical implementation limits its applicability to real-world farming conditions.

Field-based research conducted by [13] examined the effects of overhead AVS on crop productivity by monitoring environmental parameters such as temperature and light intensity. Their findings confirmed that partial shading can positively influence crop growth for certain plant types. Nevertheless, the fixed structure of the overhead panels restricts adaptability to varying crop requirements and weather conditions.

Overall, existing studies demonstrate the potential of AV to enhance land-use efficiency and sustainability, however, many proposed solutions rely heavily on simulations, require expensive and complex infrastructure, or focus primarily on energy generation while overlooking critical crop-specific requirements such as irrigation management. The summary of the limitation of previous research is listed in Table 1. To overcome these limitations, the proposed IoT-based smart light control system integrates both crop care and energy optimization into a single automated platform by employing readily available and low-cost components such as the ESP32 microcontroller and simple sensors. The system utilizes dual-axis servo motors to dynamically adjust solar panel orientation for optimal shading across diverse crop types, while an automated irrigation mechanism activates based on a 40% soil moisture threshold to ensure adequate water supply. Furthermore, the integration of the Blynk IoT platform enables real-time monitoring, alert notifications, and remote manual control, overcoming the limitations of conventional manual systems.

III. Methodology

TABLE I. Limitation of Previous Research

Title	Limitation
Development of Artificial Lighting System for Light Supplementation in Smart Greenhouses [8]	High system cost and energy consumption, expensive sensing equipment limits scalability.
Enhancing Land Use: Integrating Bifacial PV and Olive Trees [9]	Results are climate and crop-specific; limited adaptability to other agricultural settings.
Modelling and Analysis of V-Shaped Bifacial PV Systems for Agrivoltaics [10]	Heavily dependent on simulation assumptions; real-world construction cost and implementation challenges not addressed.
The Electrical Performance of a Single-Axis Sun Tracking System [11]	Focuses only on energy generation; does not consider crop shading, irrigation, or agricultural requirements.
Agricultural-Friendly Single-Axis Dynamic Agrivoltaics: Simulation Study [12]	Lacks hardware implementation and real-world validation; maintenance cost not considered.
Assessing the Impact of Overhead Agrivoltaics Systems on Crop Production [13]	Findings are site-specific; limited flexibility for different crops and varying environmental conditions.

A. System Architecture

The proposed IoT-based SLCS consists of sensing, processing, actuation, and communication layers. Fig. 1 illustrates the block diagram of proposed system. The system is organized into environmental input, central processing and control, system output, and IoT connectivity layers, with an ESP32 microcontroller acting as the main control, decision-making, and communication unit. The environmental input layer consists of four Light Dependent Resistor (LDR) sensors

for light intensity and direction detection, along with an analogue soil moisture sensor that continuously measures the volumetric water content of the soil. These sensors provide real-time data that enables the system to operate autonomously without continuous manual supervision.

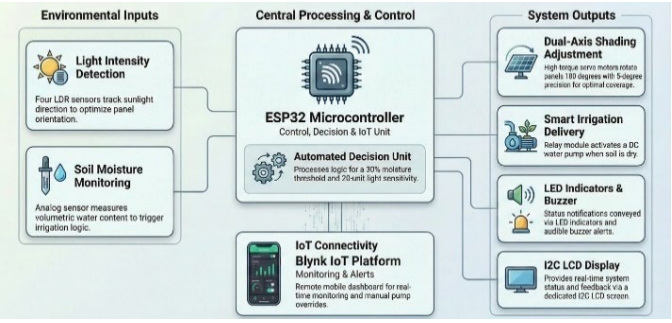

Fig. 1. Block Diagram of SLCS for AVS.

During operation, four LDR sensors are used to detect variations in sunlight along the two axes of the solar panel. The LDR readings are processed by the ESP32 using a threshold-based differential comparison method. For each axis, the light intensity difference between the corresponding LDR sensors is calculated and compared with a predefined threshold of 20. When the difference is less than the threshold, the servo motor remains stationary, and the current panel position is maintained. When the difference exceeds the threshold, the ESP32 determines the direction of panel movement according to which LDR sensor detects the higher light intensity and commands the corresponding servo motor to adjust the panel orientation. The servo motors are initially positioned at 90° and operate within a constrained angular range of 0° to 180°. Each adjustment is performed incrementally in 5° steps, after which the LDR readings are evaluated again. The adjustment process continues until the difference between the corresponding LDR readings falls below the predefined threshold, which serves as the stopping criterion for the servo motor. This iterative control allows the panel to reach the required shading orientation while avoiding unnecessary motor movement.

In parallel, the soil moisture level is continuously evaluated against the predefined threshold of 40% to determine irrigation requirements. When the soil moisture level falls below this threshold, the ESP32 activates the relay-controlled DC water pump to provide irrigation when required. A 40% soil moisture threshold was selected based on preliminary sensor calibration, prototype testing, and findings from previous studies, which indicate that suitable soil moisture thresholds vary depending on soil and vegetation conditions and may extend up to approximately 40% [14]. In this study, the 40% threshold was used to distinguish between dry and normal soil conditions and to trigger irrigation when the moisture level falls below the set value. Therefore, the selected threshold is specifically applied to the developed prototype and its experimental conditions.

In addition to local control, the ESP32 utilizes its built-in Wi-Fi capability to transmit system data to the Blynk IoT platform. This IoT connectivity allows users to monitor real-time system status, receive alert notifications during critical dry conditions, and perform manual pump overrides through a mobile dashboard. Local output devices provide immediate feedback, where an I2C LCD displays real-time soil moisture values and system status, while red and green LEDs indicate normal and alert conditions, respectively. An audible buzzer is also triggered during critical soil dryness to enhance on-site awareness.

Fig. 2 illustrates the operational flowchart of the proposed system designed primarily to prevent crops from being exposed to excessive direct sunlight. Partial shading can be beneficial for certain crops by reducing heat stress and evapotranspiration, thereby creating a more suitable microclimate for plant growth. The system begin with the sensing ambient light intensity using Light Dependent Resistor (LDR) sensors. The detected light data is evaluated to determine whether direct sunlight is excessively exposed to the solar panel. If direct light exposure is detected, the system proceeds to adjust the panel shading angle. The servo motors are activated to modify the panel orientation, and motor adjustment continues until the optimal shading position is achieved. This process ensures that the solar panels provide adequate shading for crops while maintaining effective solar energy harvesting.

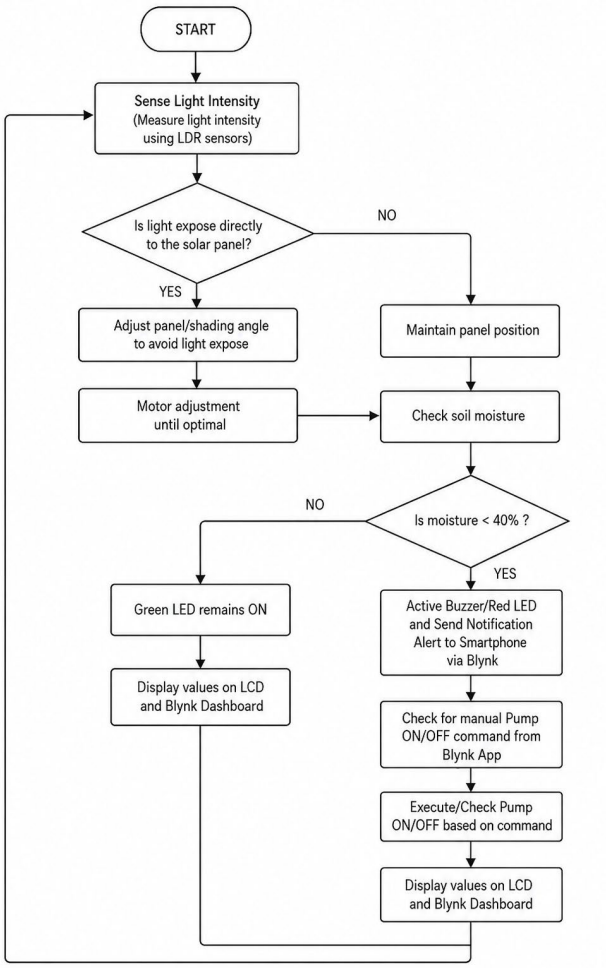

Fig. 2. Flowchart of SLCS for AVS.

If the system determines that direct sunlight exposure is not present, the solar panel position is maintained without adjustment. In both cases, the system proceeds to monitor soil conditions by checking the soil moisture level. The soil moisture value is then compared against a predefined threshold of 40%. If the moisture level is below 40%, the system identifies a dry soil condition. In response, the red LED and buzzer are activated to provide visual and audible alerts. At the same time, a notification alert is sent to the user smartphone via the Blynk IoT platform. Following this alert, the system checks for any manual pump ON/OFF commands issued through the Blynk mobile application, allowing user intervention when required. The updated system status and sensor values are then displayed on both the LCD and the Blynk dashboard. If the soil moisture level is above 40%, the system remains in a normal operating state. The green LED stays ON to indicate safe soil conditions, and no irrigation action is triggered. The current sensor readings and system status are displayed on the LCD and Blynk dashboard for continuous monitoring.

Finally, after completing the display update, the system returns to the initial light sensing stage. This loop enables continuous real-time monitoring and automatic control of shading and irrigation, ensuring optimal environmental conditions for both crop growth and AVS performance.

B. Light Intensity Detection Method

Light intensity is measured using LDR sensors connected in a voltage divider configuration. The resistance of the LDR changes according to the intensity of incident light. Eq. (1) shows the equation applied for the SLCS.

$$V_{out} = V_{cc} \times \frac{R_{fixed}}{R_{LDR} + R_{fixed}} \quad (1)$$

where: V_{cc} = supply voltage
V_{out} = output voltage read by ESP32
R_{LDR} = LDR resistance,
R_{fixed} = fixed resistor.

The ESP32 converts the measured LDR voltages into ADC readings and compares the readings from opposing LDR sensors for each tracking axis.

C. Soil Moisture Measurement and Conversion

To ensure proper irrigation management, the system continuously monitors soil moisture levels using an analogue soil moisture sensor. The sensor detects the volumetric water content in the soil by measuring changes in electrical conductivity, which vary according to moisture level. Since the raw ADC values do not directly represent percentage moisture, a calibration process is performed to convert the readings into percentage values. The conversion is expressed as in Eq. (2).

$$Moisture(\%) = \frac{ADC_{max} - ADC_{read}}{ADC_{max} - ADC_{min}} \times 100\% \quad (2)$$

where: ADC_{read} = current analog reading from the soil moisture sensor
ADC_{max} = ADC value measured in completely dry soil
ADC_{min} = ADC value measured in fully saturated soil

D. Irrigation Control Logic

The irrigation control logic is designed to ensure that crops receive sufficient water while preventing over-irrigation. The system uses the calculated soil moisture percentage obtained from the soil moisture sensor to determine whether the water pump should be activated. A fixed threshold value of 40% is implemented as the decision point. This threshold is selected to represent the minimum safe moisture level required to maintain healthy crop growth. The irrigation decision rule is defined as in Eq. (3).

$$Pump = \begin{cases} ON, & if\ moisture \leq 40 \\ OFF, & if\ moisture > 40 \end{cases} \quad (3)$$

To enable real-time shading and irrigation control in AV applications, a decision-making algorithm was implemented in the ESP32-based smart light control system. The algorithm processes the LDR and soil moisture sensor readings using predefined control parameters. For shading control, the difference between opposing LDR readings is compared with the threshold D_{th}, set to 20 ADC units. When the difference exceeds this threshold, the corresponding servo motor adjusts the panel position by the predefined *stepSize* of 5° until the light difference falls below the threshold. After the shading condition is stabilized, the algorithm evaluates the soil moisture level against the dry-soil threshold S_{dry}, set to 40%, to determine whether irrigation and alert actions are required. The shading control is given priority to reduce excessive direct sunlight exposure to crops, while the Blynk IoT platform provides real-time monitoring, notifications, and manual pump control. Table 2 summarizes the step-by-step implementation of the proposed control algorithm.

E. PCB Design and Prototype Development

Fig. 3 illustrates the printed circuit board (PCB) layout for the SLCS designed using Proteus 8 Professional. The ESP32 microcontroller is positioned at the center of the board to minimize the signal path lengths to both sensors and actuators. Dedicated header pins are assigned for input devices including the four LDR sensors and the soil moisture sensors, while separate connectors are provided for output components such as the servos, relay, and LCD.

The physical implementation of the smart AV prototype represents the final assembly stage where all hardware components, structural elements, and the control system are integrated into a functional miniature farm model as shown in Fig. 4. The central control hub is housed in a dedicated

protective enclosure, containing the ESP32 microcontroller and the custom PCB board. Water management is simulated using a raised water tank connected via tubing to the crop rows, where a DC water pump is used to automate the delivery of water based on the moisture sensor's feedback.

Dual LDR sensors are positioned strategically on the solar panel frames to accurately detect sunlight direction, while the soil moisture sensor is embedded directly into the miniature crop soil for real-time hydration monitoring. Indicators such as status LEDs and a buzzer are mounted on simulation poles to provide immediate visual and audible feedback regarding the system's operational state. The LCD display is integrated into the control box panel.

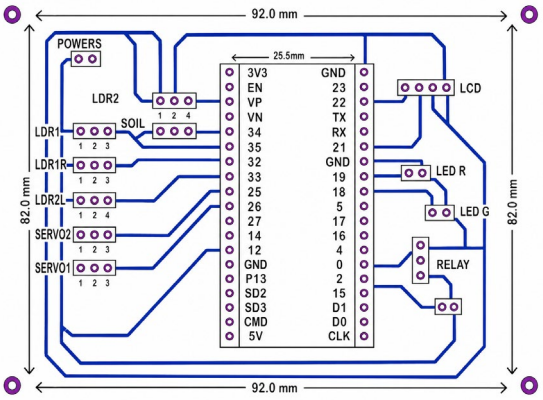

Fig. 3. PCB Design of SLCS.

TABLE 2 . PSEUDO-CODE OF SLCS

Operation
1: Initialise peripherals (Servos, LEDs, buzzer, LCD), Wi-Fi and Blynk
2: Set servo positions to 90° (initial position)
3: Set notification flag = FALSE
4: loop forever:
5: Read LDR values L_{left1}, L_{right1} for Servo #1
6: Read LDR values L_{left2}, L_{right2} for Servo #2
7: Read soil moisture sensor value ADC_{read}
#Shading Control - Highest Priority
8: Compute $diff1 = \| L_{left1} - L_{right1} \|$
9: if $diff1 > LD_{th1}$ then
10: Adjust servo1 position by ± stepSize
11: Constrain servo1 between 0° and 180°
12: end if
#Soil Moisture Evaluation
18: Convert ADC value to moisture percentage $S(\%)$
19: if $S \leq S_{dry}$ then
20: state ← DRY
21: Turn ON Red LED
22: Turn OFF Green LED
23: Activate buzzer
24: if notificationFlag == FALSE then
25: Send Blynk notification "Soil moisture is low"
26: notificationFlag ← TRUE
27: end if
28: else
29: state ← NORMAL
30: Turn OFF Red LED
31: Turn ON Green LED
32: Deactivate buzzer
33: notificationFlag ← FALSE
34: end if

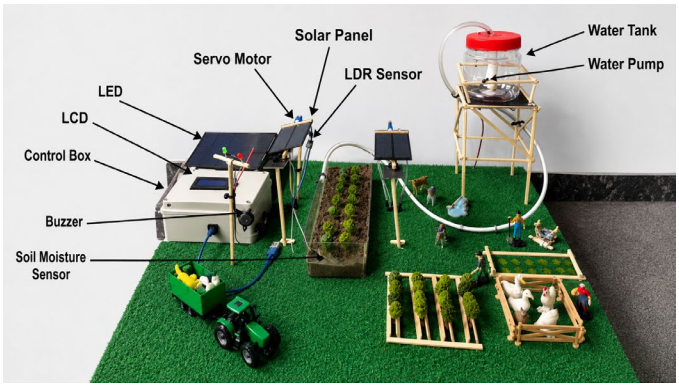

Fig. 4. Prototype of SLCS for AVS.

IV. RESULTS AND DISCUSSION

To validate the operation of SLCS, this section evaluates and analyses its performance based on light detection and shading performance, soil moisture monitoring and irrigation performance, and IoT notification performance.

Table 3 presents the experimental results for the light detection and shading control mechanism, specifically showing the relationship between LDR readings, light intensity difference, threshold comparison, and servo motor response. The results show that the servo motor remains stationary when the light intensity difference between the left and right LDR sensors is below the predefined threshold of 20. However, when the difference exceeds the threshold, the system activates the servo motor to adjust the solar panel orientation accordingly. The direction of movement is determined by which LDR sensor detects the higher light intensity. Therefore, when the LDR difference is exactly 20 ADC units, no servo adjustment is performed, and the current panel position is maintained. These results confirm the correct operation of the threshold-based shading control mechanism.

TABLE 3 . LDR DIFFERENCE ON SERVO MOTOR MOVEMENT

Left LDR	Right LDR	Difference	Threshold	Servo Movement	Final Angle
520	510	10	< 20	No movement	90
600	560	40	> 20	Adjust Right	95
450	500	50	> 20	Adjust Left	85
700	685	15	< 20	No movement	90
750	690	60	> 20	Adjust Right	100

In terms of the servo adjustment time for different angle changes, several tests were conducted to evaluate system responsiveness. As shown in Fig. 5, the adjustment time increases proportionally with the magnitude of angle change. Since the servo motor operates in fixed 5° incremental steps, larger angular corrections require additional movement cycles, resulting in longer response durations. Test 3 recorded the highest angle change (25°) and the longest adjustment time (4.0s), confirming the proportional relationship between

movement magnitude and response time.

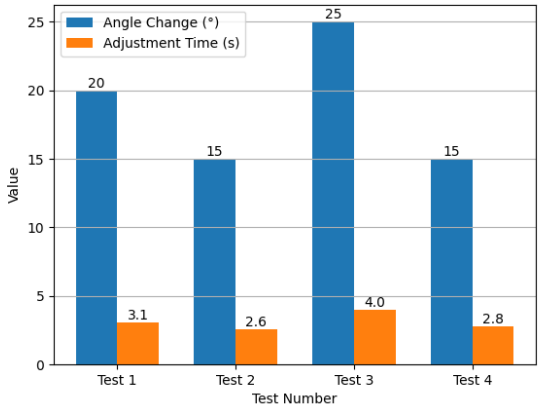

Fig. 5. Servo Adjustment Time for Different Angle Change.

To evaluate the effectiveness of the soil moisture monitoring system, experimental testing was conducted under different controlled moisture conditions. Table 4 summarizes the experimental results of the soil moisture monitoring and irrigation control system at varying moisture levels. The results confirm that the system responds accurately according to the predefined 40% threshold. When the moisture level falls at or below the threshold, the system activates the red LED, buzzer, and water pump, and sends a notification alert. When the moisture exceeds 40%, the system maintains normal operation by activating the green LED, turning the pump OFF, and suppressing notifications. This demonstrates that the threshold-based control logic functions reliably, ensuring efficient water management in the AVS.

TABLE 4 . IRRIGATION SYSTEM RESPONSE UNDER DIFFERENT MOISTURE CONDITIONS

Moisture (%)	Threshold	Red LED	Green LED	Buzzer	Pump Status	Notification
25	≤ 40	ON	OFF	ON	ON	Sent
35	≤ 40	ON	OFF	ON	ON	Sent
45	> 40	OFF	ON	OFF	OFF	Not Sent
55	> 40	OFF	ON	OFF	OFF	Not Sent
38	≤ 40	ON	OFF	ON	ON	Sent

Fig. 6 further demonstrates the real-time soil moisture percentage displayed on the mobile dashboard, showing a value of 60%, which exceeds the predefined 40% threshold. This confirms that the soil condition is within the normal operating range, and no irrigation or alert activation is required. Users can remotely track these live updates from any location as long as the ESP32 maintains a stable internet connection to the Blynk cloud. In addition to data monitoring, the interface features a virtual switch that provides the flexibility to override the automated logic and control the water pump manually.

Fig. 7 shows the real-time remote notification triggered by the Blynk platform when the soil moisture level drops below the safety threshold. When the ESP32 detects a dry condition, it utilizes the Blynk IoT cloud to push a "SOIL DRY" notification directly to the user's mobile device. The system also supports email alerts to provide a secondary layer of communication for critical environmental changes. This alert mechanism demonstrates the system's capability to provide immediate user feedback, enhancing responsiveness and ensuring effective irrigation management in the AVS.

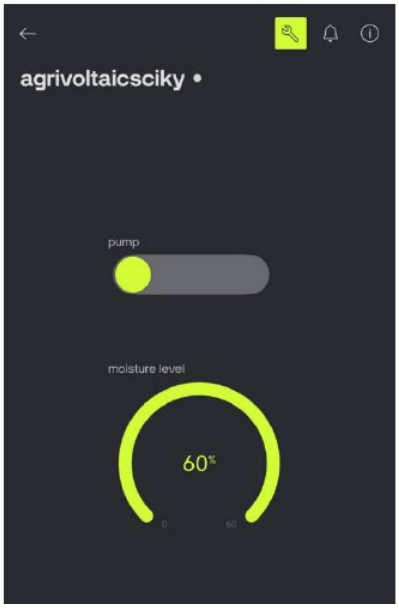

Fig. 6. Mobile Dashboard Display of Soil Moisture.

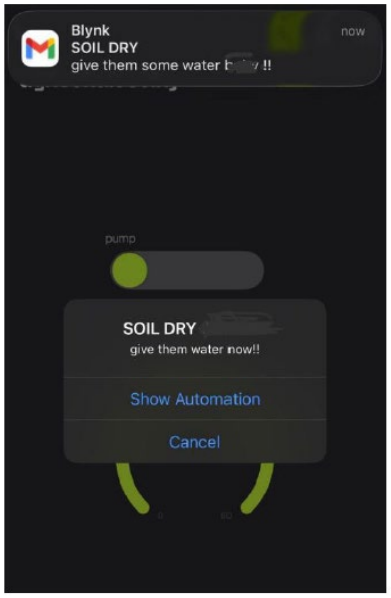

Fig. 7. Notification from Blynk Application and Email.

V. CONCLUSION

This paper introduces and experimentally validates an IoT based SLCS for AV shading optimization. The architecture employs dual environmental sensing which is illuminance and soil moisture with a threshold-based control strategy embedded within an ESP32 microcontroller. The system facilitates

continuous monitoring, automated actuator/servo motor control, irrigation management, and remote notification alerts.

Priority-based light detection ensures immediate servo-driven panel reorientation to mitigate excessive irradiance on sensitive crops. Concurrently, soil moisture measurements regulate pump activation according to a predefined 40% threshold, optimizing water utilization. Experimental evaluations verified system accuracy across all operational conditions. The shading mechanism displayed stable proportional control characteristics, with response latency correlating to angular displacement magnitude. Moisture regulation tests confirmed precise irrigation control, and IoT communication modules demonstrated dependable real-time notification delivery. These results validate the feasibility of implementing a low-cost, scalable, and energy-efficient smart AV control solution capable of enhancing crop protection while maintaining solar energy harvesting performance.

Future research should focus on long-duration field deployments, integration of multi-parameter environmental sensing such as temperature and humidity modules and incorporation of long-range communication protocols such as LoRa or GSM to support large-scale distributed deployments.

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