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A Solar-Powered Automated Alternating Wetting and Drying System for Sustainable Paddy Field Irrigation

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Alternating wetting and drying (AWD), smart irrigation system, performance solar photovoltaic (PV), water level monitoring, sustainable agriculture

Abstract

This paper presents the design and implementation of a solar-powered automated irrigation system based on the alternating wetting and drying (AWD) technique for paddy field cultivation. The system is designed to enhance water-use efficiency and reduce reliance on manual irrigation by harnessing renewable solar energy. Water level sensors are employed to monitor field conditions and automatically regulate irrigation cycles in accordance with AWD principles. A solar photovoltaic (PV) system provides renewable power to the ESP32 microcontroller and sensor, enabling reliable operation in off-grid and remote areas. Prototype testing using a scaled paddy field model is conducted to evaluate the irrigation control strategy and PV system performance. The solar PV system demonstrated a voltage range of 12.5-15.6 V, with peak power output of 99.8 W under clear-sky conditions, and exhibited a strong linear relationship between irradiance and power output (R^2 = 1.00). The automated AWD control using an ultrasonic water-level sensor achieved reliable irrigation triggering with measurement errors below 10%, enabling accurate detection of dry and normal field conditions. These results confirm that the solar-powered AWD system provides reliable off-grid operation while maintaining effective and precise water management for paddy cultivation.

1. Introduction

Rice cultivation is one of the most water-intensive agricultural practices with traditional continuous flooding methods leading to excessive water consumption and inefficient resource utilization [1]. Increasing water scarcity and labor dependency have highlighted the need for more efficient irrigation techniques, particularly in paddy field cultivation [2,3]. Alternating wetting and drying (AWD) has been widely recognized as an effective water-saving approach that maintains crop yield while reducing water usage and greenhouse gas emissions [4,5]. However, effective implementation of AWD requires continuous water level monitoring and precise irrigation control, which remain challenging under manual practices.

Recent advancements in smart irrigation systems have introduced sensor-based monitoring and automated control to improve irrigation efficiency [6-8]. Nevertheless, many existing systems rely on grid power, limiting their applicability in remote or off-grid agricultural areas [9,10]. Integrating renewable energy sources, particularly solar photovoltaic (PV) systems, can ensure the uninterrupted and sustainable operation of automated irrigation systems.

This paper presents the design and implementation of a solar-powered automated irrigation system based on the AWD technique for paddy field applications. The proposed system integrates water-level sensors with an ESP32 microcontroller to automatically regulate irrigation cycles in accordance with AWD principles. A solar PV system supplies renewable power to the sensing and control components, enabling reliable operation in remote environments [11-13]. Experimental validation using a scaled paddy field model demonstrates the feasibility and effectiveness of the proposed system for achieving water-efficient and sustainable irrigation.

2. Introduction

The proposed system consists of three main subsystems: the solar photovoltaic (PV) power supply, the irrigation actuation unit, and the sensing and control unit. The overall system architecture is designed to automatically monitor paddy field conditions and regulate irrigation based on the alternating wetting and drying (AWD) technique. A block diagram of the system is shown in Fig. 1. The ESP32 microcontroller serves as the central processing unit, receiving input from water-level sensors. Based on predefined AWD threshold values, the controller determines when irrigation is required and triggers an LED and buzzer to notify farmers.

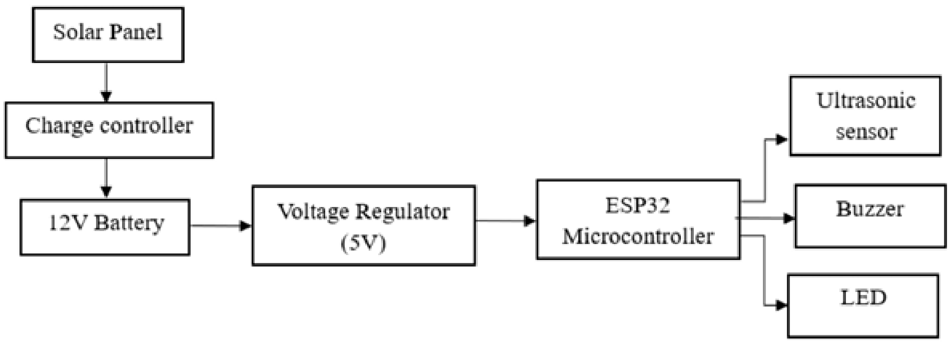


Fig. 1 *Block diagram of the project*

2.1 Solar PV System Design

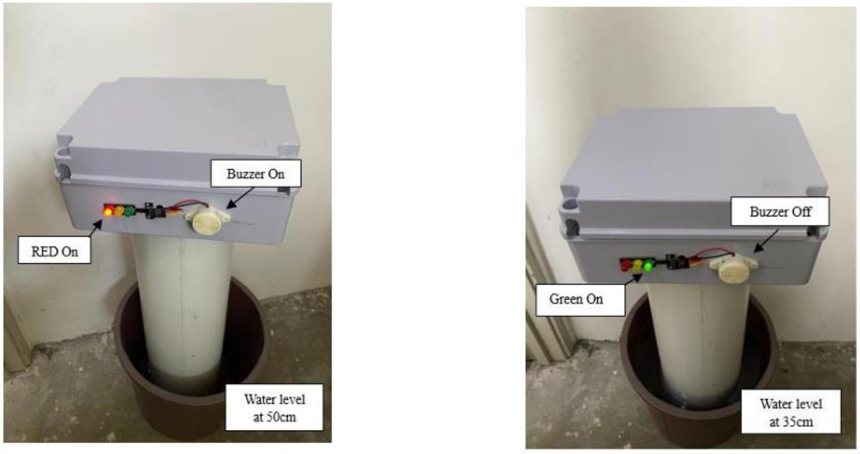
A solar photovoltaic (PV) system is integrated to provide a sustainable and off-grid power supply for the automated irrigation system. The PV system consists of a 100 W monocrystalline solar panel, a PWM charge controller, a 12 V rechargeable battery, and voltage regulation circuitry. Electrical energy harvested from the PV panel is stored in the battery and regulated to provide stable voltage levels for the ESP32 microcontroller, sensors, and buzzer.

The PV system is designed to accommodate both continuous low-power loads from the sensing and control units. The inclusion of energy storage ensures uninterrupted system operation under fluctuating environmental conditions, making the system suitable for remote agricultural applications.

2.2 Sensing and Control

The proposed system employs water-level and soil-moisture sensors to monitor paddy field conditions in real time. Water level measurement is performed using an ultrasonic sensor installed vertically within a PVC structure, enabling accurate detection of flooded and non-flooded states. Sensor data are processed by the ESP32 microcontroller, which continuously compares measured values against predefined AWD threshold levels.

Fig. 2 shows that when the water level drops to 50–60 cm, the red LED and buzzer activate, signaling that irrigation is needed. While the water level is at 30–40 cm, the green LED turns on and the buzzer stays off, indicating a normal water level where no action is required. These indicators provide clear visual and audible alerts to ensure proper irrigation timing.

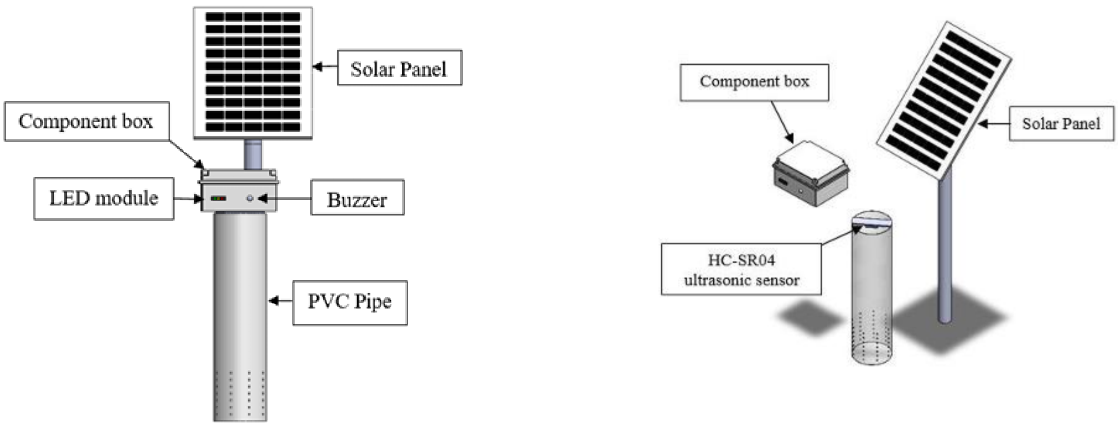


(a) **(b)**

Fig. 2 *Sensor and control (a) Dry level; (b) Normal level*

2.3 Prototype Design

Fig. 3 shows the prototype design of the solar-powered AWD irrigation system, including the front and side views of the integrated hardware structure using Autodesk simulation tools. The main assembly consists of a 60 cm-high, 6 cm-diameter PVC pipe that serves as a mounting support for the sensing and control components. A sealed component box is installed at the top of the pipe to house the 12 V battery, PWM solar charge controller, ESP32 microcontroller, LED module, and buzzer, providing protection from environmental exposure. The HC-SR04 ultrasonic sensor is mounted inside the pipe facing downward to accurately measure the water level for AWD control. A monocrystalline solar panel is positioned on a separate stand and oriented toward the sun to maximize irradiance capture and avoid shading from the main structure. This integrated design enables reliable real-time water-level monitoring and autonomous irrigation control, thereby validating the practical implementation of the AWD method under field conditions.



(a) **(b)**

Fig. 3 *Prototype design of (a) Front view; and (b) Side view*

3. Results and Discussion

3.1 Prototype Implementation

This section presents the design and physical implementation of the solar-powered automated alternate Wetting and drying (AWD) irrigation system. Fig. 4 shows the actual prototype installed in a paddy field, where the solar panel, component box, LED indicator, and PVC pipe housing the ultrasonic sensor are clearly visible. The installation site was selected at the field's corner to minimize interference with routine farming activities while ensuring effective, continuous monitoring of the water level. This location was chosen to minimize interference with routine farming activities while still allowing effective monitoring of the water level.

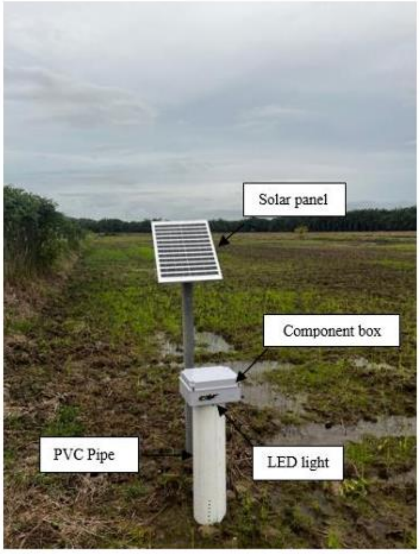


Fig. 4 *Field Installation of the solar-powered AWD irrigation prototype*

3.2 Performance Evaluation of Solar PV

3.2.1 Relationship Between Solar Irradiance and PV Output Voltage

Fig. 5 shows the relationship between solar irradiance and PV output voltage over five days, measured in the morning, at noon, and in the evening. The PV voltage ranged from 12.5 to 15.6 V, indicating relatively stable behavior. As irradiance increased, the voltage rose moderately; for example, on 19 November, irradiance increased from 512 W/m^2 at 09:00 to 998 W/m^2 at 12:45, while voltage increased from 13.0 V to 15.6 V. Similarly, on 21 November, irradiance rose from 459 W/m^2 to 913 W/m^2, causing voltage to increase from 12.7 V to 15.4 V, showing a positive relationship. However, at high irradiance (>900 W/m^2), the voltage tended to saturate at 15.0–15.6 V, indicating operation near the nominal voltage limit. Overall, PV voltage remains relatively stable despite variations in irradiance, consistent with typical photovoltaic behavior.

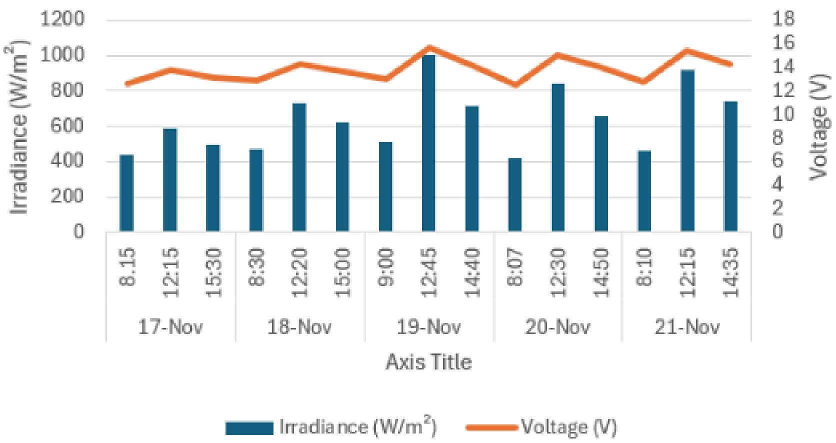


Fig. 5 *Solar irradiance vs voltage*

3.2.2 Estimated Power and Current PV Panels

Fig. 6 shows the measured PV voltage, along with the estimated current and power, from 17 to 21 November. Voltage remained relatively stable at 12.5–15.6 V despite variations in time and weather, consistent with regulated PV operation. In contrast, the estimated current varied with irradiance, increasing from 3.4–3.9 A in the

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morning to 5.6–6.4 A at midday, then decreasing in the afternoon. Estimated power followed a similar trend, ranging from 42.1–51.2 W in the morning and peaking at 99.8 W on 19 November at 12:45, corresponding to maximum voltage and current. Combined analysis shows that while voltage is stable, power variations closely follow current, confirming that the estimated current and power trends align with expected PV behavior.

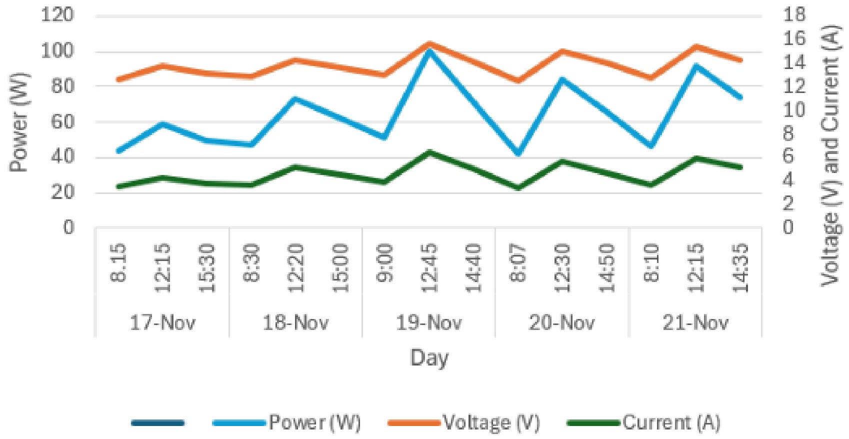

Fig. 6 *Estimation power and current*

3.2.3 Daily PV Power

Fig. 7 shows the estimated variation in PV power over five days. In all cases, power gradually increased in the morning, peaked at midday, and declined in the evening, following the daily irradiance profile. On day 1, the peak power was 58.7 W at 12:15 PM under partly cloudy conditions. Day 2 reached 73.4 W at 12:20 PM with occasional clouds. Day 3 recorded the highest power of 99.8 W, indicating clear-sky conditions. Day 4 peaked at 84.2 W under partly cloudy to hazy conditions, while day 5 reached 91.3 W with mostly clear skies. These results confirm that PV power output closely follows solar irradiance and varies with weather conditions.

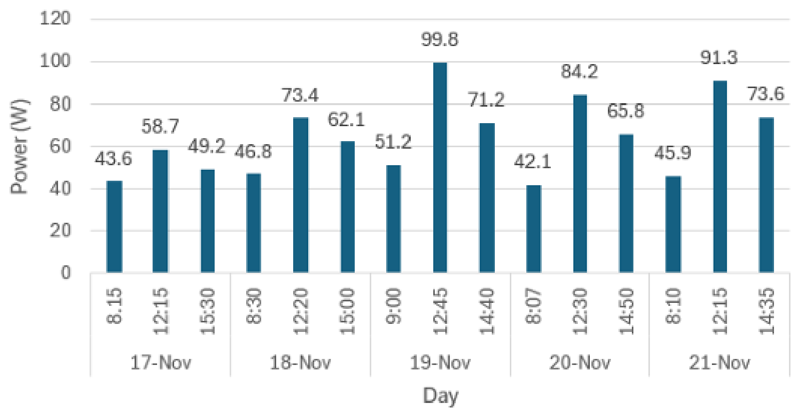

Fig. 7 *Power vs day*

3.2.4 Power Output vs Irradiance

Fig. 8 shows the relationship between solar irradiance and estimated PV power. From the figure, it is clear that PV power increases with increasing solar irradiance. This indicates a positive relationship where higher sunlight intensity results in higher power output from the PV system. A linear trendline is applied to the data to evaluate the strength of the relationship. The obtained coefficient of determination (R^2) is 1.00, indicating a strong positive correlation between solar irradiance and PV power. This means that approximately 100% of the variation in PV power is explained by changes in solar irradiance. The linear trendline equation further shows that PV power increases proportionally with solar irradiance. The slope of the trendline represents the sensitivity of PV power to irradiance. Based on the equation, an increase of 100 W/m² in solar irradiance results in an estimated increase of approximately 10 W in PV power.

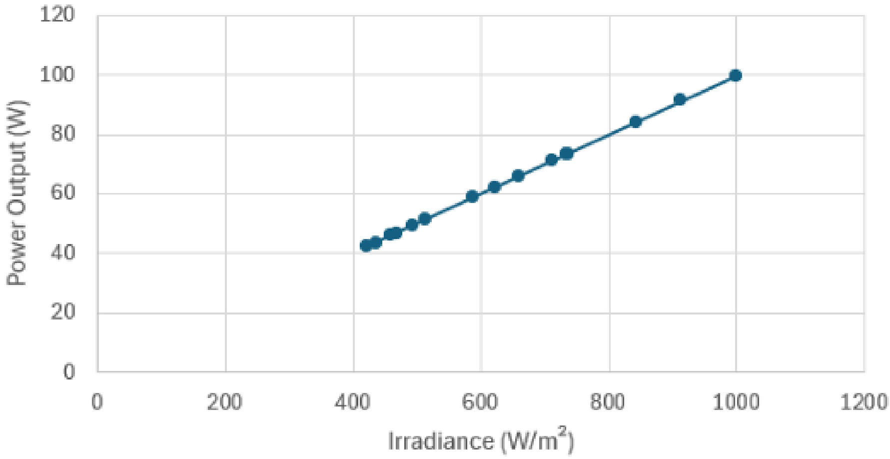

Fig. 8 *Power output (W) vs irradiance (W/m2)*

3.2.5 Current vs Irradiance

Fig. 9 shows the relationship between solar irradiance and the PV system's current output. From the figure, it can be seen that the PV current increases with increasing solar irradiance. This behavior is expected, as higher irradiance provides more energy to the PV cells, resulting in greater charge-carrier generation and, consequently, higher current output. A linear trendline is applied to the data to evaluate the strength of the relationship. The obtained coefficient of determination (R^2) is 0.998, indicating a strong positive correlation between solar irradiance and PV current. This means that approximately 99.8% of the variation in PV current is explained by changes in solar irradiance. The linear trendline equation further shows that PV current increases proportionally with solar irradiance. The slope of the trendline represents the sensitivity of PV current to irradiance. Based on the equation, an increase of 100 W/m^2 in solar irradiance results in an estimated increase of approximately 0.5 A in PV current.

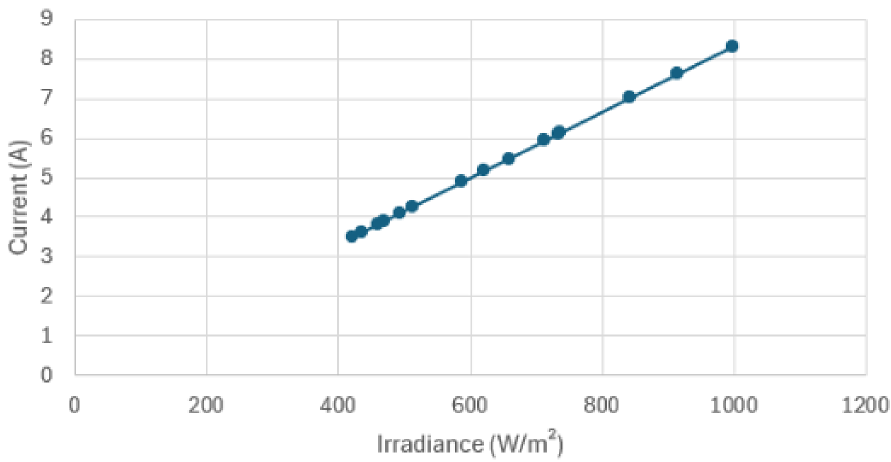

Fig. 9 *Current (A) vs irradiance (W/m2)*

3.3 Sensor Performance Evaluation

To evaluate sensor performance, the ultrasonic sensor was tested at several predefined water levels with known distances measured manually using a measuring scale. For each test point, the sensor reading was recorded and compared with the actual distance. Multiple readings were taken at each level to ensure consistency. Table 1 shows that the measured distance was slightly higher than the actual distance for all test cases. The absolute error ranged from 1 cm to 2 cm, indicating small deviations in sensor readings. When analyzed as a percentage, the error ranged from 3.33% to 10%, with higher values observed at shorter distances. This occurs because a small absolute error has a greater impact when the actual distance is small.

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Table 1 *Sensor performance testing*

Test	Actual Distance (cm)	Measured Distance (cm)	Error (cm)	Percentage error (%)
1	20	22	2	10.00
2	30	31	1	3.33
3	15	16	1	6.67
4	40	42	2	5.00

4. Conclusion

The project successfully developed a solar-powered AWD irrigation system integrated with sensors, achieving the first objective. The PV system supplied sufficient energy to the sensors and indicators, with output varying with irradiance and weather conditions. Higher irradiance increased voltage, current, and power, confirming the PV system's suitability for low-power irrigation components. The ultrasonic sensor accurately measured water levels, and the indicator system responded correctly to predefined thresholds, demonstrating effective support for AWD irrigation. Overall, the system is feasible for small-scale paddy fields and offers potential for water-efficient and sustainable irrigation.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Anis Najihah Zainol, Khairul Anuar Mohamad;* ***data collection:*** *Anis Najihah Zainol;* ***analysis and interpretation of results:*** *Anis Najihah Zainol, Khairul Anuar Mohamad;* ***draft manuscript preparation:*** *Anis Najihah Zainol, Khairul Anuar Mohamad. All authors reviewed the results and approved the final version of the manuscript.*

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