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Operational Evaluation of Automatic Watering System Based on*ESP8266*And *Blynk Cloud*with Solar Power Supply*Off-Grid*

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Abstract
Efficient water management in small-scale agricultural applications can be supported through irrigation.*loop*closed and remote environmental monitoring. This study evaluates the operational performance of a prototype automatic plant watering system based on*Internet of Things (IoT)*who uses*NodeMCU ESP8266*, *Blynk Cloud*, capacitive soil moisture sensor, temperature-humidity sensor*DHT22*, relay*active-LOW*, and 12 V DC submersible pump. Subsystem*off-grid* consisting of a 50 Wp photovoltaic module, *solar charge controller PWM*, and battery*VRLA*A 12 V 12 Ah power supply was used as the prototype power supply during testing. The system was observed for 40 hours on August 3-5, 2026, and generated 41 data records per hour without any interruption.*timestamp*Two pump actuation events were identified at recorded normalized soil moisture index values of 72.00% and 70.08%, values stored in*cloud*These values are aggregated and do not always correspond to the instantaneous values when the control triggers the pump. The soil moisture index values in subsequent recordings increased to 74.48% and 78.02%, respectively, reaching a maximum of 87.27%. Ambient temperature ranged from 23.37°C to 39.90°C, while relative humidity ranged from 50.26% to 100.00%. *Blinkshows* that 1-minute average aggregation can transform short-lived binary pump conditions into fractional values, while the visualization*MAX* or *LATEST* maintain a clearer binary display. The solar subsystem-maintained power availability throughout the test, although the photovoltaic electrical performance has not been quantitatively characterized. Overall, the prototype demonstrates automatic watering, monitoring, and*cloud*, and operations*off-grid* good during the observation period.

Keywords: *ESP8266; Internet of Things; automatic irrigation; Blynk Cloud; soil moisture; off-grid solar power.*

INTRODUCTION

Improper agricultural irrigation management can impact crop productivity, water use efficiency, and soil moisture maintenance (Bwambale et al., 2022). Conventional manual irrigation often relies on visual observation or fixed schedules, which can lead to over-watering or under-watering (Vallejo-Gómez et al., 2023). Over-irrigation can increase water loss and nutrient leaching, while insufficient watering can cause water stress in plants and stunt their development (Obaideen et al., 2022). Automatic plant watering system using control*loop*A closed-loop relay is used to regulate water supply based on measured soil conditions (Mustofa & Sunardi, 2023). Threshold-based control can activate the pump when the measured soil moisture index falls below a predetermined lower limit and deactivates it once the upper limit is reached. This approach reduces manual intervention while preventing the relay from rapidly switching repeatedly around a single threshold value (Muthuramalingam et al., 2024).

*Internet of Things (IoT)*extending the functionality of automatic irrigation through wireless monitoring, remote supervision, and data exchange between field devices and services*cloud*(Gzar et al., 2022). *ESP8266*widely used in prototypes*IoT*low cost because it integrates connectivity*Wi-Fi*with embedded control capabilities (Ramli & Jabbar, 2022). In irrigation applications, this device can acquire sensor signals, execute local control logic, control actuators, and transmit operational data to a monitoring platform. Platform based*cloud* like *Blink*supports real-time visualization and historical recording of environmental variables and irrigation (Saputri et al., 2025). Historical recording is useful for evaluating variations in soil moisture, microclimate conditions, and actuator responses during the observation period (Chamara et al., 2022). However, data aggregation on the*cloud*can affect the display of short-duration binary actuator events in exported data as well as*dashboard*, so these effects need to be considered in interpreting control performance.

In agricultural locations without reliable access to the electricity grid, photovoltaic energy and battery storage can be an alternative power supply for controllers, sensors, communication devices, and irrigation equipment (Obaideen et al., 2022; Borges et al., 2024). Therefore, the irrigation prototype*IoT*Solar-powered systems have been studied as both standalone and portable systems (Al Mamun et al., 2025). In this study, a photovoltaic subsystem was used as a supporting power supply.*off-grid,* electrical conversion efficiency and energy yield are beyond the scope of this test.

Previous research has shown the application of water-based irrigation control. *ESP8266*, monitoring*Blink*, telemetry*IoT*, and solar-powered irrigation in various combinations (Wanyama et al., 2023). This study focuses on system-level operational evaluation by integratedly examining threshold-based pump response, environmental monitoring, and continuity of water recording.*Blynk Cloud*, the influence of aggregation*cloud*to the binary status of the pump, as well as continuous operation using solar power supply*off-grid*. Thus, the objectives of the study were to evaluate the automatic pump response, characterize the recorded soil moisture and microclimate behavior, and assess the continuity and effects of data aggregation.*Blink*, and verified the uninterrupted operation of the prototype during a 40-hour test.

METHOD

The experimental prototype was assembled using the hardware and software summarized in Table 1. A capacitive soil moisture sensor was used as a low-cost indicator to monitor changes in water conditions in the growing medium. Because the capacitive sensor output is affected by soil properties and measurement conditions, calibration is required before the signal can be interpreted as volumetric water content (Adla et al., 2024; González-Teruel et al., 2022; Li et al., 2022; Mane et al., 2024; Wanyama et al., 2023). In this study, the sensor output was normalized between a dry air reference and a full immersion reference in water. Therefore, the reported soil moisture values are treated as a normalized relative soil moisture index (%) and not as a direct measurement of volumetric water content.

Table 1. Hardware and software specifications of the automatic plant watering prototype

Subsystem / Component	Interface	Function
Main operator —*NodeMCU ESP8266 V3 (32-bit, 80 MHz, Wi-Fi 2,4 GHz)*	System bus	Central control and*gateway IoT Wi-Fi*
Soil sensing — Capacitive soil moisture sensor v1.2 (analog output)	A0	Normalized soil moisture index sensing
Climate sensing —*DHT22* / *AM2302*	GPIO4 / D2	Ambient temperature and relative humidity monitoring
Actuator switch — 1-channel 5 V DC relay*active-LOW*	GPIO5 / D1	Controlling 12V pump load
Water actuator — 12 V DC submersible pump	Relai COM / NO	Distribution of water to the planting medium
Solar PV panel — Polycrystalline module, 50 Wp	Terminal PV *charge controller*	Energy input*off-grid*
Charge controller — PWM, 10 A, 12 V DC	Battery / load terminals	Battery charging and power management
Energy storage — Batteries*VRLA*AGM, 12 V 12 Ah	Bus daya 12 V	Energy storage*off-grid*
Step-down regulator — LM2596, 12 V to 5 V DC	COME*ESP8266*/ VCC relay	5 V logic power supply
Firmware And *cloud* — *Arduino IDE C++*, *Blynk Cloud API*	Virtual Pin V0–V6	Control logic, telemetry, and visualization

RESEARCH SCHEME

The system architecture consists of four functional layers supported by solar panel resources.*off-grid*, namely the sensing layer, control layer, actuation layer, and telemetry layer*IoT*The sensing layer consists of a capacitive soil moisture sensor and a digital temperature-humidity sensor. *DHT22*The control layer consists of a microcontroller*NodeMCU ESP8266*and 1-channel 5 V DC relay module*active-LOW*The actuation layer uses a 12 V DC submersible water pump connected to a water reservoir. The telemetry layer*IoT*using IEEE 802.11 b/g/n Wi-Fi connection,*Blynk Cloud*, as well as web and mobile monitoring dashboards. The system architecture is shown in Figure 1.

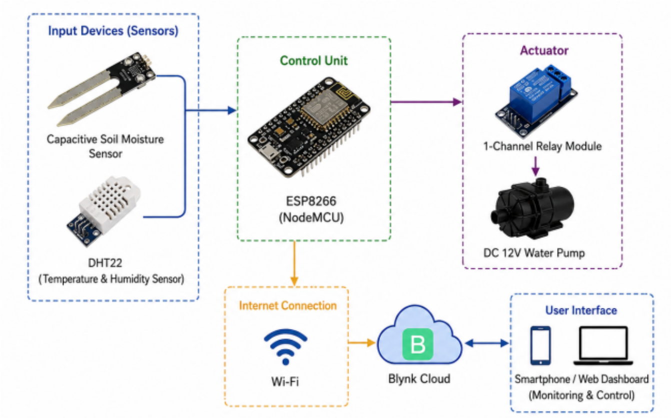

Figure 1. IoT architecture of an automatic plant watering system based on ESP8266 powered by off-grid solar power supply.

The hardware electrical connections are shown in Figure 2. Wireless communication is required to transmit agricultural sensor information from devices in the field to the remote monitoring platform in a smart farming system based on*IoT*. In this prototype, Wi-Fi provides a communication path between*ESP8266* And *Blynk Cloud*.

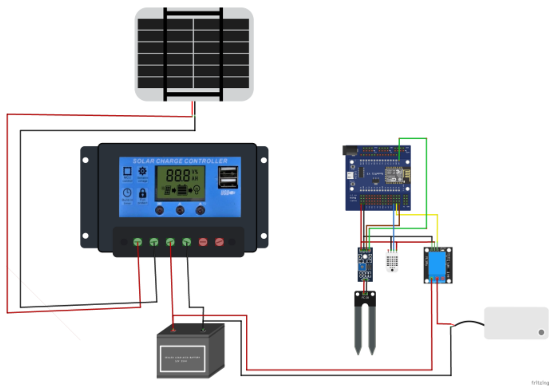

Figure 2. Automatic plant watering system hardware wiring diagram

Control Algorithms and Telemetry

*Firmware ESP8266*run control algorithm*loop*closed. Raw value*analog-to-digital converter (ADC)*read at pin A0 is mapped into a normalized soil moisture index, SM (%), using Equation (1):

$$SM = constrain(map(ADC, 1023, 300, 0, 100), 0, 100) \quad (1)$$

With *ADC*is the raw analog reading, 1023 is the dry air reference mapped to 0%, and 300 is the full immersion reference mapped to 100%. These reference points produce a normalized sensor index and are not a calibration of the soil volumetric water content. The automatic watering decision uses a two-threshold hysteresis strategy. The pump is activated when SM ≤ 70%, deactivated when SM ≥ 80%, and the previous relay state is maintained when 70% < SM < 80%, as summarized in Equation (2):

$$\text{Relay Output(GPIO5)}=\{\text{LOW (Pump ON), if SM} \leq 70\%\ \text{HIGH(Pump OFF), if SM} \geq 80\% \quad (2)$$

Because the relay module uses logic*active-LOW*, giving conditions*LOW*on GPIO5 activates the relay coil and closes the pump circuit. The hysteresis band reduces*switching ON/OFF*repeats when the sensor value fluctuates around a single threshold value.

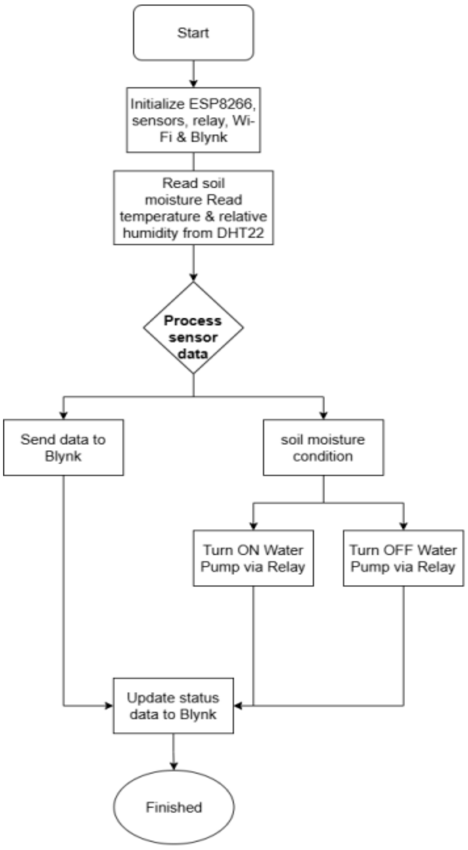

Figure 3. Flowchart of automatic irrigation system control algorithm.

*ESP8266*send system parameters to*Blynk Cloud*through the network*Wi-Fi*. The recorded variables consist of soil moisture index on Virtual Pin V0, relative humidity on V1, ambient temperature on V2, operation mode on V3, manual pump control on V4, pump operation status on V5, and pump duration on V6. *Dashboard Blink*used to display system conditions and environmental data remotely. Appearance *dashboard Blynk Cloud*used for remote system monitoring is shown in Figure 4.

Figure 4. Blynk Cloud dashboard view for remote system monitoring

Experimental Design and Data Analysis

The prototype was applied to a single growing medium container to evaluate operational performance. Testing was conducted from August 3, 2026, at 10:00 a.m. WIB to August 5, 2026, at 2:00 a.m. WIB, for a total observation period of 40 hours.*Blynk Cloud*The data were then analyzed into 41 hourly recordings. The 41 recordings were obtained because the recordings included the initial and final time points of the observation interval. Testing focused on control system response, environmental monitoring, data continuity, and operation.*off-grid* The test does not include calibration of soil volumetric water content, direct measurement of irrigation discharge, or quantitative characterization of photovoltaic energy.

Figure 5. Arrangement of experimental components during system testing

Data exported from*Blynk Cloud*processed using*Python*pandas. Based on 41 hourly recordings, the arithmetic mean (x̄), sample standard deviation (s), minimum, median, and maximum values for the normalized soil moisture index, ambient temperature, and relative humidity were calculated. The arithmetic mean and sample standard deviation are expressed in Equations (3) and (4). Pearson correlation was also calculated to quantify the relationship between ambient temperature and relative humidity.

$$\bar{x} = \frac{\Sigma_{i=1}^{n} x_i}{n} \quad (3)$$

$$s = \sqrt{\frac{\Sigma_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \quad (4)$$

RESULTS AND DISCUSSION

Soil Moisture Monitoring

The normalized soil moisture index was monitored over a 40-hour observation period. The hourly dataset consisted of 41 recordings from 10:00 a.m. WIB on August 3, 2026, to 2:00 a.m. WIB on August 5, 2026. Values ranged from 70.08% to 87.27%, with an average of 81.28% ± 4.05% (sample standard deviation). The complete hourly dataset is presented in Table 2.

Table 2. Environmental sensor data and pump actuation status recorded hourly (N = 41 recordings)

Time	Humidity Index Land (%)	Temperature (°C)	KR (%)	Pump
10:00	81,76	32,74	64,90	0
11:00	78,96	34,71	59,13	0
12:00	77,42	38,74	53,67	0
13:00	77,94	39,90	50,44	0
14:00	75,47	37,50	54,41	0
15:00	72,00	34,42	62,20	1
16:00	74,48	31,59	71,84	0
17:00	71,38	29,08	78,80	0
18:00	70,08	27,81	85,72	1
19:00	78,02	27,12	87,58	0
20:00	80,45	26,27	90,60	0
21:00	80,92	26,13	92,51	0
22:00	81,16	25,93	94,54	0
23:00	81,40	25,70	95,82	0
00:00	81,44	25,02	98,74	0
01:00	81,37	24,96	100,00	0
02:00	81,48	24,50	100,00	0
03:00	81,50	24,07	100,00	0
04:00	81,49	23,87	100,00	0
05:00	81,49	23,37	100,00	0
06:00	81,59	24,36	99,78	0
07:00	82,60	26,44	94,16	0
08:00	83,75	28,06	85,42	0
09:00	84,40	29,86	77,75	0
10:00	85,51	32,22	70,03	0
11:00	86,70	36,96	57,59	0
12:00	87,27	39,00	50,26	0
13:00	87,24	39,15	53,81	0
14:00	86,92	37,10	57,69	0
15:00	85,88	34,09	62,65	0
16:00	84,96	31,38	68,68	0
17:00	84,05	28,87	77,87	0
18:00	83,40	27,38	84,28	0
19:00	82,65	26,65	88,50	0
20:00	82,52	26,52	90,68	0
21:00	82,40	26,71	90,11	0
22:00	82,40	26,14	94,06	0
23:00	82,30	26,10	94,99	0
00:00	82,19	26,03	94,32	0
01:00	81,85	25,75	94,10	0
02:00	81,70	25,57	94,96	0

As shown in Table 2, the normalized soil moisture index decreased from 81.76% at 10:00 AM to 72.00% at 3:00 PM on August 3. The first recorded pump actuation occurred at 3:00 PM, with subsequent hourly recordings increasing to 74.48%. The second actuation was recorded at 6:00 PM when the hourly value was 70.08%; subsequent recordings increased to 78.02% at 7:00 PM and 80.45% at 8:00 PM. On August 4, the index remained above 81% and reached a maximum recorded value of 87.27% at 12:00 PM. These results indicate moisture recovery after both recorded irrigation events, although hourly aggregation cannot depict the instantaneous trajectory of sensor values during pump operation. Variations in the soil moisture index and recorded pump actuation events are shown in Figure 6.

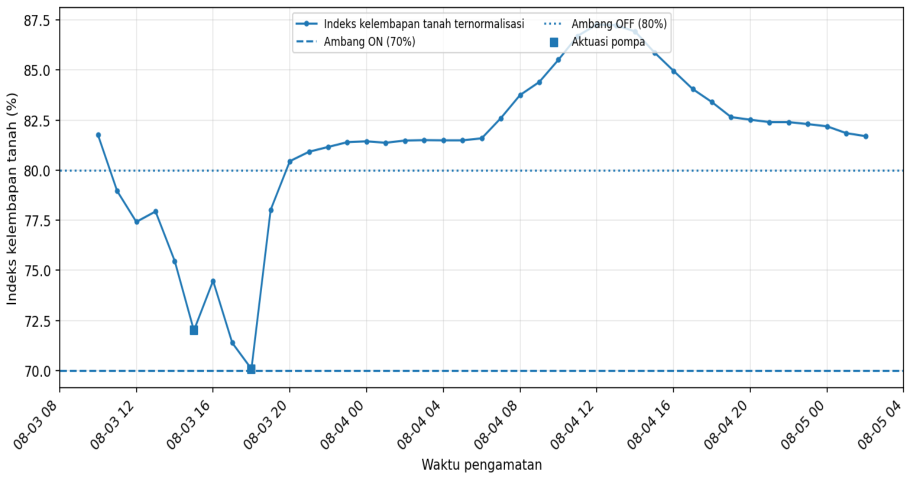

Figure 6. Variations in normalized soil moisture index, control thresholds, and recorded pump actuation events.

Automatic Pump Response

Two automatic irrigation events were identified in the export dataset, as summarized in Table 3.2.

Table 3. Observed automatic irrigation events and recorded soil moisture index values

Time	Recorded SM (%)	Next SM (%)	Results
1. 2026-08-03 15:00	72,00	74,48	ON pump; ΔSM +2.48 pp
2. 2026-08-03 18:00	70,08	78,02	ON pump; ΔSM +7.94 pp
Rate-rate	71,04	76,25	ΔSM +5,21 pp

The control system successfully executed both recorded pump actuations. The soil moisture index value in subsequent hourly recordings increased by 2.48 percentage points after Event 1 and 7.94 percentage points after Event 2, with an average increase of 5.21 percentage points for both events. After the index reached 80.45% at 8:00 PM on August 3, no additional pump actuations were recorded until 2:00 AM on August 5, representing another 30 hours of operation without additional recorded irrigation events.

The recorded value of 72.00% in Event 1 is higher than the threshold*ON*momentarily by 70% at*firmware*. This condition should not be interpreted as a conflicting control decision because the values at*cloud*is a recording of the aggregated results and not the raw sensor values at the exact moment the trigger occurs.*Blink*configured with a 1-minute average aggregation, while the analysis dataset is reduced to hourly recordings. As a result, short trajectories that cross thresholds and pump events may experience smoothing within the recording window.*cloud*. High-frequency raw telemetry is required to precisely quantify control response delays and trigger values.

Temperature and Relative Humidity

Microclimate parameters recorded by the sensor*DHT22*summarized in Table 3.3.

Table 4. Summary statistics of environmental variables (N = 41 records)

Parameter	Rate-rate	SB	Min	Median	Max
Soil Moisture Index (%)	81,28	4,05	70,08	81,70	87,27
Ambient Temperature (°C)	29,46	5,02	23,37	27,12	39,90
Relative Humidity (%)	81,04	16,94	50,26	87,58	100,00
Pump Actuation Status (0/1)	0,05	0,22	0	0	1

Ambient temperature ranged from 23.37°C to 39.90°C, while relative humidity ranged from 50.26% to 100.00%. Both variables exhibited a very strong inverse relationship (Pearson's r = -0.987).

The highest temperature occurred at 1:00 PM on August 3 (39.90°C) when relative humidity was 50.44%, while nighttime temperatures decreased to a minimum of 23.37°C at 5:00 AM on August 4 when relative humidity reached 100.00%. The same inverse pattern was observed on August 4, when the 1:00 PM temperature of 39.15°C coincided with a relative humidity of 53.81%. This relationship provides a microclimatic context for interpreting changes in the normalized soil moisture index during the test. The variations in ambient temperature and relative humidity are shown in Figure 7.

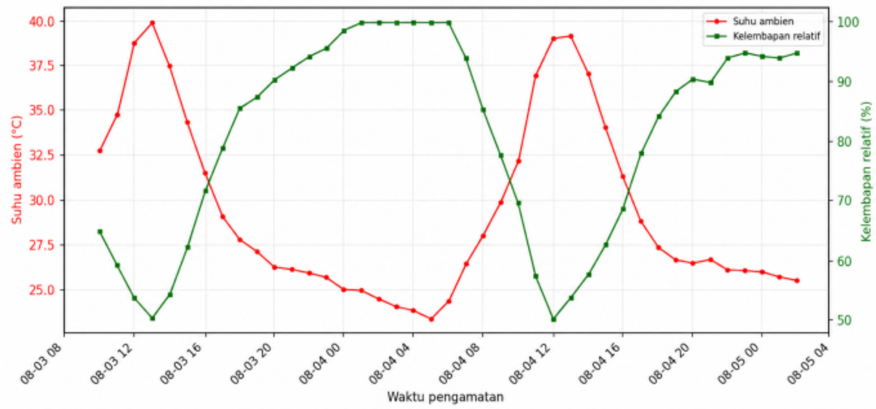

Figure 7. Ambient temperature and relative humidity during the observation period

Monitoring and Continuity*Blynk Cloud*

*Blynk Cloud*can provide remote monitoring and historical data storage during testing. Data logging continuity is summarized in Table 5.

Table 5. Blynk Cloud data logging summary

Metric	Recorded	Target	Status
Expected hourly observations	41 recordings	41 recordings	100%
Hourly observations received	41 recordings	41 recordings	100%
Missing hourly intervals	0 recordings	0 recordings	Complete
Data continuity level	100,00%	100,00%	Complete

The exported dataset contains all 41 expected hourly observations without*timestamp*lost, so that the continuity level in the analyzed period reaches 100%. Virtual Pin Mapping sends the normalized soil moisture index (V0), relative humidity (V1), ambient temperature (V2), and pump status (V5) to the console.*cloud*. These results verify the continuity of the recordings analyzed during the 40-hour test, but do not constitute a measurement of communication reliability or latency at the packet level.

Chart analysis*cloud*The export results identify the aggregation effect when the pump binary status (V5) is saved using the 1-minute average setting on*Blink*. If the pump is in the ON state only during part of the aggregation window, temporal smoothing may produce fractional values such as 0.5, instead of discrete values of 0 or 1. Visualization settings*dashboard* become *MAX* or *LATEST*displays a clearer representation of binary steps without changing the underlying database records. This finding is important when short-duration actuator conditions are interpreted from the data.*IoT*which have been aggregated in*cloud*.

Overall System Performance

During 40 hours of testing, the prototype was able to integrate soil condition sensing, threshold and hysteresis-based pump control, temperature and relative humidity monitoring via sensors. *DHT22*, and data recording through*Blink Cloud*The test dataset consists of 41 hourly recordings with no missing timestamps, allowing the entire analyzed observation period to be represented in the exported data. Two pump actuation events were identified on August 3, 2026, at 3:00 PM and 6:00 PM. Following these two events, the soil moisture index recorded in the subsequent period increased by 2.48 and 7.94 percentage points, respectively. After reaching 80.45% at 8:00 PM, no additional pump actuation events were recorded until the end of the observation period. These results indicate that the automatic control function can operate based on changes in soil moisture conditions measured during the test.

In terms of environmental monitoring, the system is capable of recording ambient temperature in the range of 23.37–39.90 °C and relative humidity in the range of 50.26–100.00%. The Pearson correlation between ambient temperature and relative humidity shows a very strong negative linear relationship with a value of (r=-0.987). These results indicate that the system can not only be used to control irrigation based on the soil moisture index but can also provide information on microclimate conditions during the observation period.

On the telemetry side, all 41 expected hourly recordings were successfully obtained without any missing intervals, resulting in a 100% continuity rate for the analyzed data. However, interpretation of pump status requires consideration of the characteristics of data aggregation.*Blink Cloud*. Using a 1-minute average aggregation on the pump status variable can convert ON events that last only part of the time window into fractional values, such as 0.5. Therefore, the export results*cloud*does not always represent the binary status of the pump at any given time. Using the MAX or LATEST visualization settings can provide a clearer view of the binary status on the dashboard but does not change the underlying aggregated data. This finding suggests that the configuration of the recording and aggregation methods*cloud*care must be taken when telemetry data is used to evaluate actuator response.

The power supply subsystem consists of a 50 Wp photovoltaic module, a PWM charge controller, and a battery. *VRLA*12 V 12 Ah. During the observation period, the subsystem was able to maintain the prototype's operation without utility grid support. These results indicate power availability during the test conditions but cannot yet be used to determine photovoltaic conversion efficiency, daily energy consumption,*state of charge*battery, or system autonomy because voltage, current, energy generation, and load consumption were not measured quantitatively. Thus, the contribution of the solar subsystem to this study was limited to providing a power supply to support the prototype's operation during the testing period.

Functionally, the system developed has characteristics that are in line with previous research that applies*Internet of Things*for soil moisture monitoring, automatic watering control,*Blink*or platform*cloud*, as well as solar energy sources. Research by Mustofa and Sunardi (2023) implemented automatic irrigation based on*ESP8266* And *Blink*, whereas Muh. Owen M. et al. (2025) developed a soil moisture monitoring and irrigation control system based on*IoT* use *Blink*. Saputri et al. (2025) developed a water-based irrigation monitoring and control system.*Blink* and *ThingSpeak*On the energy side, Borges et al. (2024), Ramli and Jabbar (2022), and Al Mamun et al. (2025) demonstrated the application of solar energy sources in irrigation systems based on*IoT*.

Compared to previous research, this study is not aimed at claiming increased irrigation efficiency or higher photovoltaic performance. The main contribution of the study lies in the operational evaluation of the integration. *ESP8266*, soil moisture sensor, sensor*DHT22*, hysteresis-based pump control,*Blink Cloud*, and solar power supply*off-grid* in one prototype. In addition, this study explicitly identifies the influence of data aggregation*cloud*on the representation of the binary actuator status. The results show that the evaluation of the system*IoT*It is not enough to simply check for successful data delivery, but it is also necessary to consider how the data is stored and aggregated before being used to interpret system responses.

CONCLUSION

This study evaluates the operational behavior of a prototype of automatic plant watering based on*ESP8266*which is monitored through*Blynk Cloud*and supplied by a photovoltaic-battery subsystem*off-grid*. During the 40-hour test, 41 observations were obtained per hour without*timestamp*Two automatic pumping events were recorded, and the normalized soil moisture index values in subsequent recordings increased by 2.48 and 7.94 percentage points, respectively. The normalized index ranged from 70.08% to 87.27%. Ambient temperature ranged from 23.37°C to 39.90°C, and relative humidity ranged from 50.26% to 100.00%, with a very strong inverse correlation (r = -0.987).*Blynk Cloud*supports continuous remote monitoring, while 1-minute average aggregation has been shown to produce fractional representations for short-duration pump binary conditions visualization*MAX* or *LATEST*provides a clearer binary view. Solar subsystem*off-grid* maintain power availability during testing, but the electrical performance of photovoltaics has not been evaluated quantitatively. The results of the study indicate the feasibility of integrating local threshold control, monitoring*cloud*, and power supply*off-grid* on a compact smart farming prototype, while longer tests and higher resolution measurements are still needed to generate broader performance claims.

DECLARATION OF GENERATIVE AI

The authors declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

CONFLICTING INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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AUTHORSHIP CONTRIBUTION STATEMENT

Nanda Mikola: Conceptualization, Methodology, Writing - Original Draft. **Deni Fajar Fitriyana**: Methodology, Formal Analysis, Writing - Review & Editing, Supervision, Resources, Validation.

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