

Original Research Paper

Implementation of Solar Energy for an IoT-Based Agricultural Irrigation and Monitoring

Budy Gunawan^{1*}, Rini Puji Astutik¹

¹ Department of Electrical Engineering, Faculty of Engineering, Universitas Muhammadiyah Gresik. Gresik, Indonesia.

Article History

Received:
21.11.2025

Revised:
13.12.2025

Accepted:
24.12.2025

*Corresponding Author:

Budy Gunawan

Email:
budykencrut@gmail.com

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Abstract: In Indonesia, there are approximately 27,368,114 households that work as farmers. Generally, farmers use diesel-fueled pumps for rice field irrigation, but in the current era, diesel is becoming scarce. Trials have been conducted with electric pumps, but they are not supported in areas far from residential areas. Therefore, in this research, a pump drive system was created using an induction motor controlled by an ESP32, with sensor integration for monitoring, solar energy as the Power supply, and the BLYNK application for remote monitoring. The results of the study show that solar panels can produce 580.6 Watts of Power in 8 hours, with a maximum Power of 87.4 Watts at 100,000 lux and 35°C. The sensor accuracy is also perfect, with an average error below 2%. The system also successfully regulated automatic irrigation based on soil moisture levels using the Capacitive Soil Moisture v1.2 sensor: the pump turns on when soil moisture is <40% and stops when it is >60%. Scientifically, this research contributes to the development of an intelligent irrigation system based on solar energy and IoT for remote agricultural areas. However, the control system remains static and is not fully adaptive to changing environmental conditions. Therefore, further research is recommended to integrate artificial intelligence methods, such as fuzzy logic or machine learning, to enhance the system's flexibility and performance across diverse soil conditions. With these developments, this system could become an innovative and sustainable agricultural solution in areas without access to PLN electricity.

Keywords: BLYNK, ESP32, IoT, Renewable Energy, Smart Irrigation.



1. Introduction

Indonesia is an agricultural country, with the majority of its population relying on the agricultural sector for their livelihood, especially in rural areas [1]. In Indonesia, tens of millions of households work as farmers [2]. As reported on the Indonesian Central Bureau of Statistics website. Agricultural processing is inseparable from irrigation systems, which aim to regularly and efficiently circulate water to agricultural land to maintain optimal productivity [3].

Currently, farmers still use diesel-fueled pumps [4]. However, fuel prices continue to rise due to declining domestic crude oil production [5]. As recorded on the Ministry of Energy and Mineral Resources website, the cost of diesel fuel, which was originally Rp5,500, has now risen to Rp7,500.

To address this issue, trials using electric pumps have been conducted. However, further problems arise in remote areas where there is no PLN electricity network to supply the pumps' energy needs [6]. If this problem is not resolved immediately, farmers will likely switch professions, leading not only to rising fuel prices but also to higher food prices.

A previous study by Pamuji et al. (2024) on an integrated On-Grid Photovoltaic water pump system and electrification of rice fields to reduce irrigation costs [7]. The results of this study indicate that with the help of solar panels, it can reduce operational costs incurred by farmers regarding water problems, but the system used is still less than optimal in its maintenance because it is not equipped with a monitoring system and still uses a Power supply from PLN [8].

Another study conducted by Alam et al [9] on the planning of SPP for rice field irrigation pumps in Ulak Aurstanting Village, Pemulatan Selatan District, Ogan Ilir Regency. Based on the research, 50 solar panels with a capacity of 500 W are required to Power two pump units to meet the water needs of 20 ha of rice fields. However, this study did not implement automation in the system's operational method, nor did it integrate the system with an Internet of Things (IoT) platform; therefore, the approach is considered suboptimal for application in the current era [10].

Based on the problems encountered, this research aims to develop a diesel pump drive system using a single-phase induction motor integrated with an off-grid Photovoltaic System to provide continuous electricity from renewable, environmentally friendly energy [11]. With this research, it can reduce the burden of farmers' expenses regarding rice field irrigation problems, where this system is also equipped with automation and connects it to the Internet of Things (IoT) platform in the form of BLYNK, so that farmers can monitor the condition of the irrigation system even though they are not at the rice field location [12]. This research contributes to the development of sustainable IoT- and renewable energy-based agricultural automation systems.

2. Literature Review

2.1. Solar Panels

Solar panels, or photovoltaic modules, are renewable energy devices that convert solar radiation into electrical energy via the photovoltaic effect in semiconductor materials [13]. Solar panel performance depends on several key factors, including solar radiation intensity, panel surface temperature, tilt angle, and weather conditions [14]. In off-grid solar Power systems, solar panels are generally combined with batteries and solar charge controllers to maintain a stable energy supply [15]. Various studies have shown that the use of solar panels in irrigation systems can increase energy efficiency and is a viable solution for remote agricultural areas without access to conventional electricity [7] [8] [9].

2.2. Single-Phase Induction Motor

Single-phase induction motors are alternating current motors commonly used as water pump drives due to their simple construction, reliability, and low maintenance costs [16]. These motors require auxiliary circuits, such as capacitors, to produce starting torque and are classified based on their starting method [17]. Several studies have shown that single-phase induction motors can operate stably in off-grid solar Power systems, making them suitable for irrigation applications in remote areas without access to conventional electricity [16] [18].

2.3. Centrifugal Pump

Centrifugal pumps are dynamic pumps that use centrifugal force to move fluids from the suction side to the discharge side [19]. These pumps offer simple construction, relatively high discharge capacity, and ease of maintenance, making them widely used in irrigation systems [20]. Various studies have shown that centrifugal pumps operate reliably and efficiently when driven by induction motors, making them suitable for use in renewable energy-based irrigation systems, including off-grid solar power systems

[21] [22].

2.4. ESP32

The ESP32 is an embedded system-on-chip microcontroller equipped with a high-performance processor, diverse I/O interfaces, and wireless communication support, including WiFi 802.11 b/g/n and Bluetooth version 4.2 [23]. Several studies have shown that the ESP32 can integrate sensor data acquisition, actuator control, and real-time data communication into a single centralized system [24]. Therefore, the ESP32 is considered suitable for use as the central controller in the renewable energy-based innovative irrigation system in this study, especially for remote monitoring and control [23] [24] [25].

2.5. Electronic Sensors for Monitoring Systems

Electronic sensors are an essential component of a monitoring system that detect and measure physical and environmental parameters in real time [26]. In this study, the researchers used multiple sensor types, including the Capacitive Soil Moisture Sensor v1.2 to detect soil moisture levels in rice fields [27], the DHT11 sensor as a temperature and humidity detector on the solar panel control box [28], the RPM Meter (Tachometer) sensor used to determine the motor rotation speed when the system is working [29], the Flowmeter sensor used to determine the water discharge released by the diesel pump when the system is working [30], the PZEM-004t sensor used to determine the amount of Power generated by the solar panel [31], and the LDR sensor used to detect the intensity of sunlight absorbed by the solar panel [32]. Various studies have shown that the use of electronic sensors in monitoring systems can improve the efficiency of water and energy management and support adaptive, sustainable system control [25] [26] [27] [30].

2.6. BLYNK

BLYNK is an Internet of Things (IoT) platform that provides an application-based interface for remote monitoring and control of electronic devices over the internet [33]. This platform supports integration with various microcontrollers, including the ESP32, and enables real-time visualization of sensor data and actuator control [34]. Several studies have reported that using BLYNK in agricultural monitoring and automation systems can improve ease of monitoring, control flexibility, and operational efficiency in innovative irrigation systems Powered by renewable energy [25] [33] [34].

3. Methodology

3.1. System Design

The system design provides an overview of the components used as inputs and outputs, along with the process stages from start to finish. The overview, presented as a system block diagram, is shown in Figure 1.

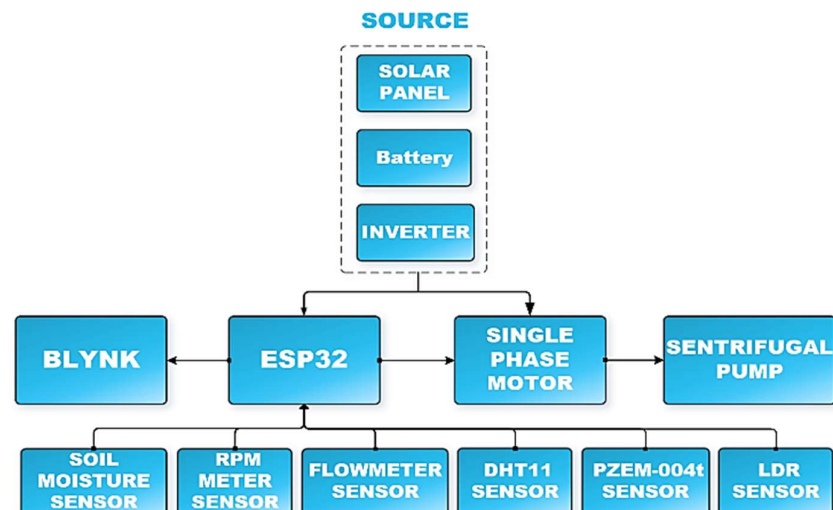


Figure 1. System Block Diagram

Figure 1 shows that several sensors are used as inputs, namely the soil moisture sensor, RPM meter sensor, flowmeter sensor, DHT11 sensor, PZEM-004t sensor, and LDR sensor. All sensor data will be sent to the ESP32 microcontroller for processing.

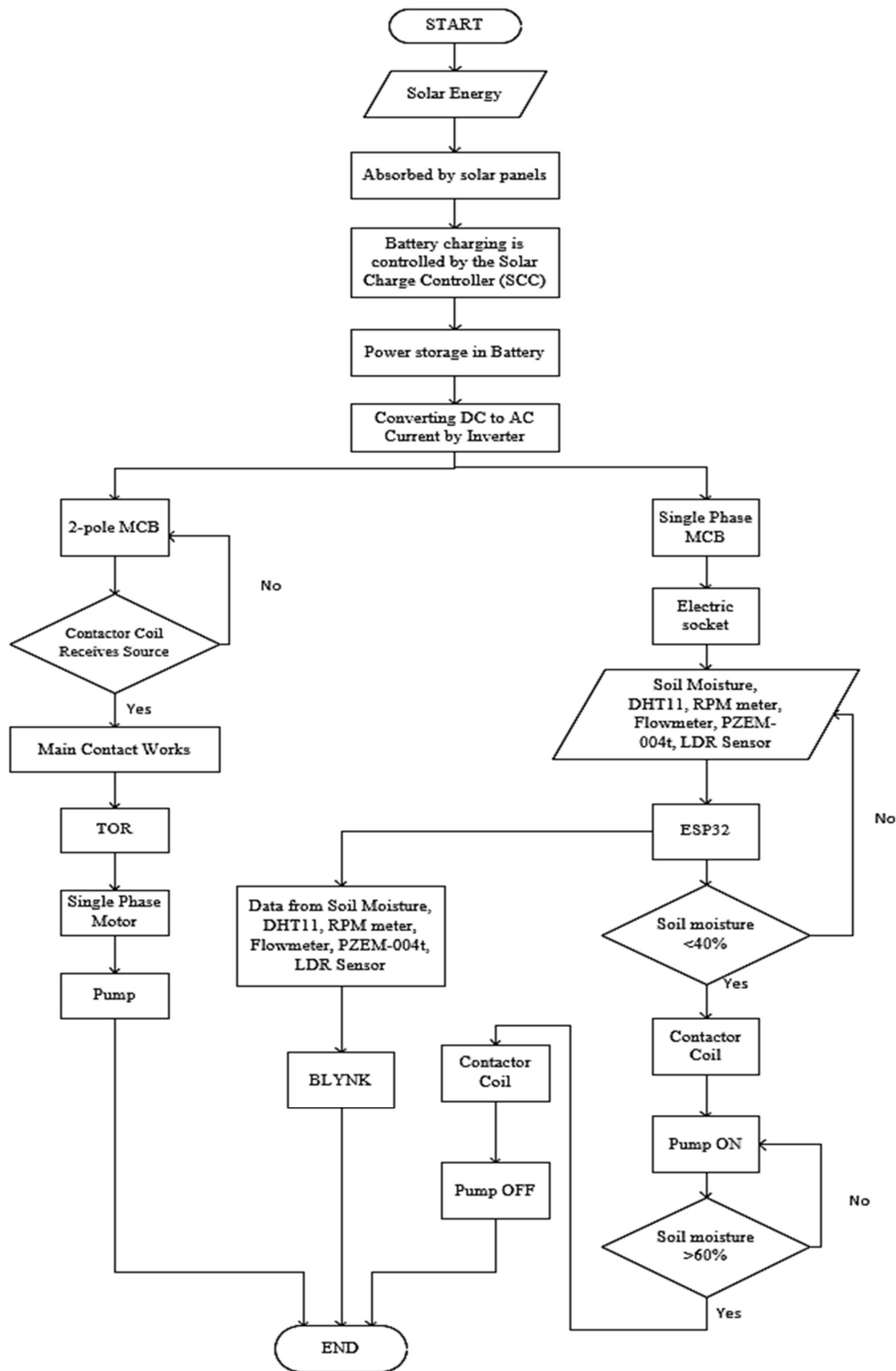


Figure 2. System Work Flowchart

The sensor data received by the ESP32 microcontroller is forwarded to the BLYNK application for remote monitoring. A single-phase induction motor is used as a centrifugal pump driver, driven by commands from the ESP32 microcontroller. The electrical energy required by the ESP32 microcontroller and the single-phase induction motor is supplied by a solar Power generation system. An explanation of the tool's overall working system is shown in Figure 2.

Figure 2 shows that the system begins with the absorption of solar energy converted into Direct Current (DC) electrical energy by solar panels; the electrical energy produced is stored in the ACCU via a Solar Charger Controller (SCC) to prevent overcharging or overdischarging. The DC current from the ACCU is first converted to Alternating Current (AC) by a DC-to-AC inverter before being connected to a single-phase MCB and a 2-pole MCB. The current from the single-phase MCB is routed to the Power outlet as a Power source for the ESP32 via a 5V adapter and a contactor coil. After the ESP32 receives Power, data from each sensor will be read, and the resulting data will be sent to the ESP32 for processing. Data from the soil moisture sensor is in the form of a soil moisture value as a determinant of system operation; namely, if the soil moisture value is >40%, the sensor reading will continue to repeat until the soil moisture value is <40%, then the ESP32 microcontroller will command the contactor coil to turn on the pump until the soil moisture value is >60%. The ESP32 sends all data generated by the sensor to the BLYNK application so the condition of the irrigation system can be monitored remotely. In the BLYNK application, the display of the values generated by each sensor can be configured according to the user's preferences. A 2-pole MCB is used as a connector for the single-phase induction motor Power source via a contactor coil controlled by ESP32, namely the primary contact of the contactor, which is initially Normally Open (NO) and will change to Normally Closed (NC), and the electric current flows to the single-phase induction motor through the Thermal Overload Relay (TOR) as a safeguard against overheating when the motor is working. The single-phase induction motor Powers the pump, allowing it to flow water to the rice fields because the motor shaft is connected to the pump shaft, so the pump rotates when the motor is running.

3.2. Solar Panel Planning

Solar panel design significantly impacts the efficiency and effectiveness of electrical energy use, so solar panel and battery capacity must be considered, along with inverter selection. A detailed explanation includes:

1) Solar Panel Calculation

This point explains the calculation of solar panels as a Power supply for 1 day. The calculation begins by determining the amount of Power used using Equation (1).

$$Wh = P \times h \tag{1}$$

Where:

Wh = Power consumption/day (Watt hours)

P = Load power used (watts)

h = Hourly usage (hours)

The Power capacity of each component over an assumed 12-hour period is shown in Table 1.

Table 1. Power Required by the System

No	Components	Power (Watts)	Usage (Hours)	Total	Total Power (Wh)
1	Single-Phase Induction Motor	750	2	1	1,500
2	Contactor	10	2	1	20
3	ESP32 Microcontroller	1.25	12	1	15
4	1-Channel Relay Module	0.4	12	1	4.8
5	Capacitive Soil Moisture Sensor v1.2	0.05	12	1	0.6
6	DHT11 Sensor	0.0125	12	1	0.15
7	RPM Meter Sensor	0.1	12	1	1.2
8	Flow Meter Sensor	0.075	12	1	0.9
Total:					1,542.65

Based on Table 1, the total Power required by the system is known, so the capacity of the solar panels used can be calculated. Optimal solar energy absorption occurs during the day, when the sun's rays are perpendicular to the solar panels, and the temperature is relatively high, specifically from 09.00-14.00 WIB. The capacity of the solar panels can be calculated using Equation (2).

$$Wp = Wh / 5 \text{ hours} \quad (2)$$

where:

Wp = Solar panel capacity (Watt peak)

Wh = Power usage/day (Watt hours)

The calculation result using Equation (2) is $1,542.65 / 5 \text{ hours} = 308.53 \text{ Wp}$, so that the system can work optimally, a solar panel capacity of 400 Wp is used. The selection of solar panel type must also be considered, as each panel significantly affects the system's efficiency. The solar panel used in this study is a polycrystalline silicon solar panel because it is relatively inexpensive and can achieve an efficiency of 17%.

2) Battery Capacity Calculation

Calculating battery capacity is essential to store electrical energy from solar panel absorption, and the stored energy will be used when the system requires an electrical Power supply. Battery capacity can be determined using Equation (3).

$$Ah = Wh / V \quad (3)$$

where:

Ah = Battery Capacity (Ampere-hours)

Wh = Daily Usage (Watt-hours)

V = Voltage (Volt)

Based on Equation (3), the required battery capacity is $1,542.65 \text{ Wh} / 12 = 128.55 \text{ Ah}$. To ensure optimal operation, a 12V 200Ah battery is used, with a total Power of $12V * 200Ah = 2,400 \text{ Watts}$.

3) Inverter Capacity Calculation

Inverters convert DC current to AC so the Power source can be applied to a single-phase induction motor. The inverter capacity can be calculated using Equation (4).

$$P_{total} = W_{max} + (25\% \times W_{max}) \quad (4)$$

where:

P_{total} = Total required power capacity (Watts)

W_{max} = Peak load power (Watts)

25% = Safety factor/reserve power to accommodate initial starting currents (inrush current)

From Equation (4), an inverter capacity of $1,542.65 \text{ Wh} + (25\% * 1,542.65 \text{ Wh}) = 1,928.3125 \text{ Watts}$, or 2,000 Watts, is required for the system to operate optimally.

In the inverter, there is lost Power, or the amount of Power lost when the system is operating, which is calculated using Equation (5).

$$P_{loss} = P_{in} - P_{out} \quad (5)$$

where:

P_{loss} = Power lost (Watts)

P_{in} = Input power (Watts)

P_{out} = Power out (Watts)

P_{in} comes from the total Power produced by the battery, which is 2,400 Watts, while to determine the P_{out} value, Equation (6) is used.

$$P_{out} = P_{in} \times \text{Efficiency} \quad (6)$$

The inverter efficiency is 90%, so the P_{out} is $2,400 \text{ watts} \times 90\% = 2,160 \text{ watts}$. The total Power loss in this study is $P_{loss} = 2,400 - 2,160 = 240 \text{ W}$; when expressed as a percentage, it is $(240/2,400) * 100 = 10\%$.

3.3. Hardware Design Planning

Hardware design planning is a description of the hardware design used as a benchmark for implementing the system in the real world. The explanation is as follows.

1) Design of Motor Connection with Pump

The type of connection selected in this study is a flexible coupling type, namely by positioning the motor and pump parallel to the base plate to minimize changes in position due to vibration when the motor rotates. The motor and pump shafts are connected with a coupling and tightened using nuts on each side of the circle so that there is no change in torque when the motor rotates. Torque can be calculated using Equation (7).

$$T = \frac{9550 \times P}{n} \quad (7)$$

where:

T = Nominal motor torque (Nm)

P = Motor power (kW)

n = Motor rotational speed (rpm)

The illustration of the motor and pump connection planning design is shown in Figure 3.

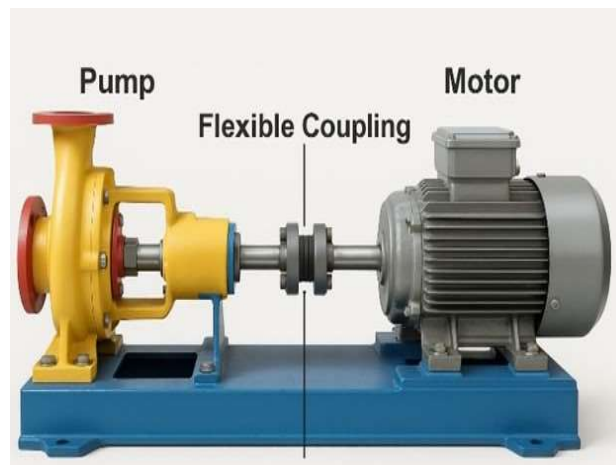


Figure 3. Motor Connection with Pump

2) Monitoring System Design

A monitoring system design helps understand electronic circuits during implementation. This design consists of input, process, and output components, as seen in Figure 4

Figure 4 shows six sensors as inputs and relays as outputs connected to the ESP32 microcontroller on different pins. The soil moisture sensor is connected to GPIO pin 34, the DHT11 sensor is connected to GPIO pin 14, the RPM meter sensor is connected to GPIO pin 12, the flowmeter sensor is connected to GPIO pin 13, the PZEM-004t sensor is connected to the Tx and Rx pins, the LDR sensor is connected to GPIO pin 27, and the relay is connected to GPIO pin 17.

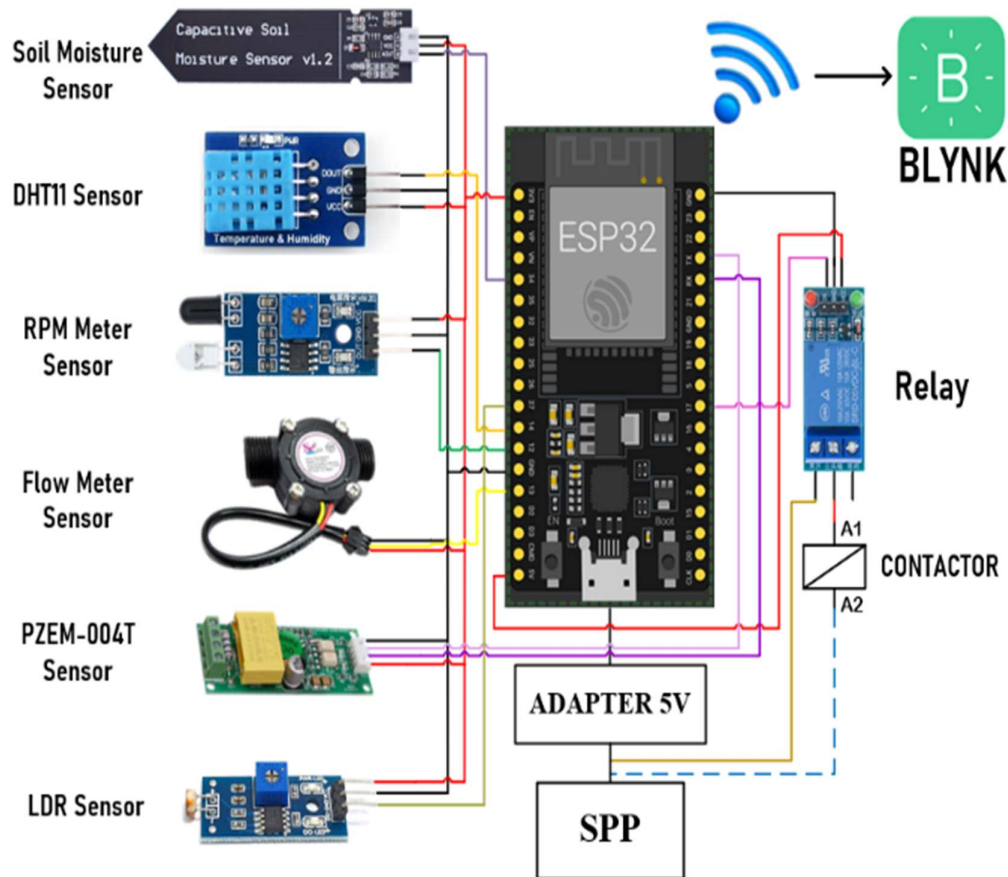


Figure 4. Monitoring System Design

The ESP32 microcontroller was chosen for this process because it has a built-in WiFi module for sending data from each sensor to the BLYNK application, which will later be used for remote monitoring. The Power supply for the ESP32 microcontroller is provided by a 5V adapter from the Solar Power Plant (SPP) output.

3.4. Software Design Planning

The software design includes all input components used to monitor the system in real time via BLYNK. BLYNK is an application that allows creating a Graphical User Interface (GUI) on smartphones by selecting buttons, sliders, graphics, and other widgets without having to make a display from scratch. The BLYNK application can be used by programming the ESP32 microcontroller in the Arduino IDE using the C/C++ language.

The integration between the software architecture and the user interface is presented in Figure 5, which details the BLYNK application program code, and Figure 6, which illustrates the resulting BLYNK app view.

```
sempro | Arduino 1.8.19
File Edit Sketch Tools Help
sempro $
#include <WiFi.h>
#include <BlynkSimpleEsp32.h>

char auth[] = "AUTHENTICATION"; // Replace with your authentication
char ssid[] = "WIFI_NAME"; // Replace with your Wi-Fi name
char pass[] = "WIFI_PASSWORD"; // Replace with your Wi-Fi password

#define LED_PIN 2 // Use GPIO 2 (ESP32 internal LED)

BLYNK_WRITE(V0) {
  int pinValue = param.asInt(); // Value of the virtual button (0 or 1)
  digitalWrite(LED_PIN, pinValue);
}

void setup() {
  Serial.begin(115200);
  pinMode(LED_PIN, OUTPUT);
  digitalWrite(LED_PIN, LOW); // LED turns off at startup
  Blynk.begin(auth, ssid, pass);
}

void loop() {
  Blynk.run();
}
```

Figure 5. BLYNK Application Program Code

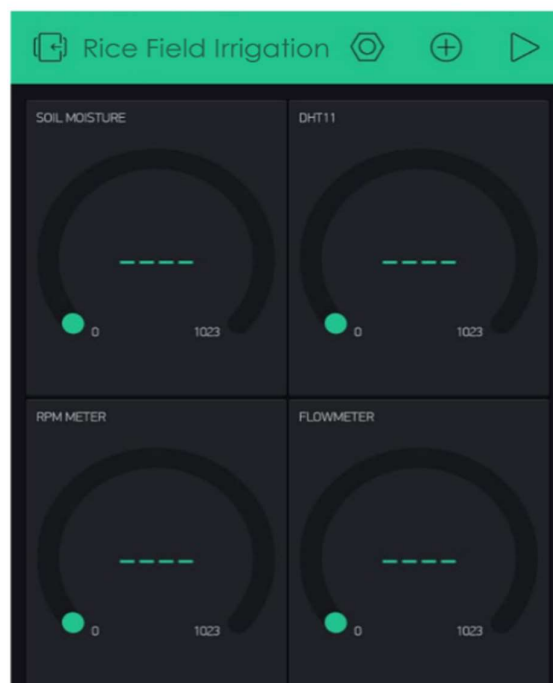


Figure 6. BLYNK App View

4. Finding and Discussion

After the prototype was developed, testing was conducted, including sensor and solar panel testing, as well as overall system performance testing. This testing aimed to evaluate system performance and ensure its suitability for the design objectives. All testing was conducted in the rice fields of Ketapanglor Village, Ujungpangkah District, Gresik Regency, East Java, Indonesia. The test data was then analyzed to assess system performance and reliability. The results of the prototype are shown in Figure 7.



Figure 7. Prototype for an IoT-Based Irrigation Controller Driven by Solar Energy

4.1. Sensor Testing

Sensor testing involves comparing sensor output with reference (actual) values to evaluate system accuracy and effectiveness. In this study, six sensors were tested ten times, and the measurement error was calculated as a percentage using Equation (8). The average error for each sensor was then determined using Equation (9). The test results for each sensor are presented in Figure 8.

$$E = \frac{(\text{Real Value} - \text{Sensor Value})}{\text{Real Value}} \times 100 \quad (8)$$

$$R = \frac{1}{10} \sum_{n=1}^{10} E \tag{9}$$

where:

- E = error in one test data (%)
- R = average error of one sensor (%)
- N = test (1-10)

Figure 8 shows a relatively minimal average error on each sensor, namely the Capacitive Soil Moisture Sensor v1.2 of 0.65%, the DHT11 sensor of 1.67%, the RPM meter sensor of 0.97%, the flow meter sensor of 0.97%, the PZEM-004t sensor of 0.68%, and the LDR sensor of 1.03%.

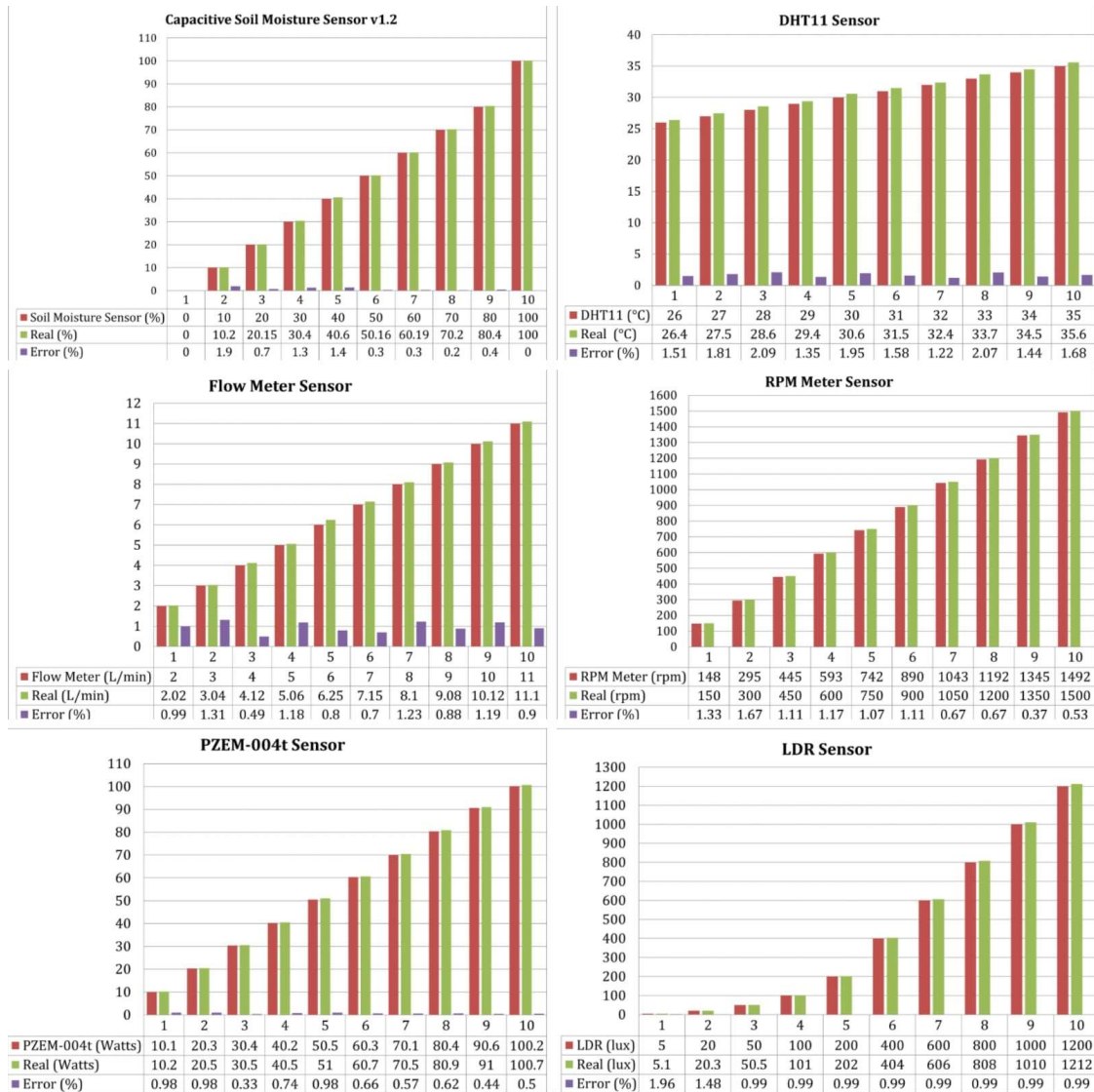


Figure 8. Sensor Testing

Once the average error for each sensor is known, the average error across all sensors can be determined using Equation (10).

$$K = \frac{1}{6} \sum_{m=1}^6 R \tag{10}$$

where:

K = Average error of all sensors (%)

R = Average error of one sensor (%)

M = Sensor (1-6)

The calculation using Equation (10) yielded an average error of 0.99%, indicating that the sensor exhibits high measurement accuracy. This result is consistent with the findings of Abdinoor et al. (2025), who reported that the manufacturer-specified tolerance range for sensor error is 1%-3% [35].

4.2. Solar Panel Testing

The next stage is solar panel testing. This testing is conducted to determine the voltage, current, and Power generated by the Solar Power Generation System (SPP) based on the intensity of sunlight received. The solar panel testing process is shown in Figure 9.



Figure 9. Solar Panel Testing

Figure 9 shows solar panels arranged parallel to the building's roof to obtain optimal solar exposure and minimize the risk of loss if placed in a rice field. The solar panel test results are presented in Table 2.

Table 2. Solar Panel Test Data

Time (WIB)	Voltage (V)	Current (A)	Power (Watts)	Light Intensity (Lux)	Temperature (°C)
08:00	16.5	2.1	34.7	25,000	28
09:00	17.0	3.0	51.0	45,000	30
10:00	17.5	4.2	73.5	70,000	32
11:00	18.0	4.6	82.8	90,000	34
12:00	18.2	4.8	87.4	100,000	35
13:00	18.0	4.5	81.0	95,000	35
14:00	17.6	4.0	70.4	80,000	34
15:00	17.1	3.3	56.4	55,000	32
16:00	16.7	2.6	43.4	30,000	30

According to Table 2, the solar panel test lasted 8 hours, from 8:00 to 16:00 WIB. The highest Power generated, 87.4 watts, occurred at 12:00 WIB when the light intensity reached 100,000 lux, and the panel temperature reached 35°C. During the test, the total Power generated by the solar panel reached 580.6 Wh. These results indicate that the Power generated is directly proportional to the intensity of sunlight, adjusting to conditions during the day as the ambient temperature increases.

4.3. Overall Tool Testing

The final test was the overall system test. This test was conducted to determine the compatibility between the hardware and software used. This test included the integration of the Solar Power Plant (SPP), the sensors used, the monitoring system, and the automatic control system for rice field irrigation. The results of the overall equipment test are shown in Table 3.

Table 3. Overall Test Results Data

Time (WIB)	SPP			Sensor Soil Moisture (%)	Sensor DHT11 (°C)	Sensor RPM Meter (rpm)	Sensor Flow Meter (L/min)	Sensor LDR (Lux)	Pump
	V	A	P						
08:00	16.00	2.00	34.0	50	27.8	0	0	24,540	OFF
09:00	16.54	2.80	49.8	48	29.5	0	0	44,307	OFF
10:00	16.97	4.00	70.8	44	31.6	0	0	69,765	OFF
11:00	17.89	4.50	81.4	40	33.8	0	0	88,532	OFF
12:00	18.00	4.75	85.6	35	34.5	1,484	738	97,689	ON
13:00	17.87	4.42	80.7	48	33.8	1,496	746	94,267	ON
14:00	17.23	3.80	69.8	61	34.0	0	0	78,542	OFF
15:00	16.67	3.20	55.4	60	32.7	0	0	53,865	OFF
16:00	16.00	2.49	41.8	58	29.8	0	0	27,865	OFF

Based on Table 3, the maximum voltage, current, and Power generated by the solar panel reached 18 V, 4.75 A, and 85.6 W, respectively, at 12:00 WIB, when the sunlight intensity was 97,689 lux, and the temperature was 34.5°C. In the automatic irrigation system, the soil moisture sensor detects a gradual decrease in soil moisture levels as the surrounding environment warms. When soil moisture is <40% at 12:00 WIB, the pump runs until soil moisture >60% at 13:00 WIB. Readings from the RPM and flow meter sensors then follow the pump. The implementation of the tool in the rice field area is shown in Figure 10.



Figure 10. Pump and Motor Placement

In Figure 10, the pump and motor are placed facing the rice field to facilitate irrigation, and a panel box containing a monitoring and automation system is placed near the pump and motor to help farmers perform maintenance. Each sensor is placed at a separate point: the soil moisture sensor is placed on the rice field soil, the DHT11 sensor is placed in the panel box, the RPM meter sensor is placed on the base plate between the pump and motor connections, the flow meter sensor is placed at the end of the water outlet pipe to the rice field, and the PZEM-004t sensor and LDR sensor are placed on the solar panel area. Data generated by the sensors when the system is operating will be sent in real time to the BLYNK application, as shown in Figure 11.



Figure 11. BLYNK Display When the System is Working

Figure 11 shows that the solar energy optimization system, as an IoT-based agricultural irrigation and monitoring system, has worked optimally, starting from sensors and microcontrollers to solar Power systems.

5. Conclusion

This study demonstrates that integrating an off-grid Solar Power Plant (SPP) with an automated irrigation system and IoT-based monitoring is a technically feasible and contextually relevant solution to support agricultural activities in areas not yet connected to the PLN electricity grid. Test results show that all sensors used have high accuracy, with an average measurement error below 2%, enabling the system to provide reliable data for real-time irrigation decision-making. In terms of energy performance, the SPP system generated 580.6 Wh during the eight-hour test period, with a maximum Power of 87.4 Watts at a light intensity of 100,000 Lux and a panel temperature of 35 °C. These findings confirm that solar energy can be effectively used as the primary Power source to operate an induction-motor-based irrigation system in remote agricultural areas, thereby reducing dependence on fossil fuels and lowering farmers' operational costs.

In practice, implementing an automatic irrigation system based on soil moisture (<40% for pump activation and >60% for pump shutdown) has been shown to improve water-use efficiency and reduce the need for manual intervention. The integration of an IoT platform via the BLYNK application makes it easy for users to monitor land conditions and system performance remotely, thereby enabling more efficient, responsive agricultural management. However, the implemented control system is still static because it relies on threshold-based logic. This approach is not fully able to accommodate the dynamics

of the agricultural environment, including variations in soil characteristics, changes in climate, and differences in water requirements at each stage of plant growth. Therefore, further research is recommended to integrate artificial intelligence methods, such as fuzzy logic or machine learning-based approaches, and to systematically design and support them with historical data analysis to improve the system's adaptability and autonomy.

Overall, this research provides scientific and practical contributions to the development of intelligent irrigation systems Powered by renewable energy and IoT, and opens opportunities for further development towards the implementation of sustainable precision agriculture, especially in rural areas with limited access to electrical energy.

References

- [1] Q. Ayun, S. Kurniawan, and W. A. Saputro, "Perkembangan Konversi Lahan Pertanian Di Bagian Negara Agraris," *Vigor J. Ilmu Pertan. Trop. Dan Subtrop.*, vol. 5, no. 2, pp. 38–44, 2020.
- [2] R. Tirtalistyani, M. Murtiningrum, and R. s. Kanwar, "Indonesia Rice Irrigation System : Time for Innovation," *Sustainability*, vol. 14, no. 19, pp. 1–19, 2022.
- [3] R. Binayao and P. V. Mantua, "Smart Water Irrigation for Rice Farming through the Internet of Things," *Int. J. Comput. Sci. Res.*, vol. 8, no. 1, pp. 2550–2563, 2024.
- [4] Z. Aini, Kunaifi, A. Wanda, E. Ismaredah, and W. Anjarjati, "Solar Irrigation System in Indonesia: Practical Assessment and Evaluation for Converting Fossil Fuels with Solar Energy," *IOP Conf. Ser. Earth Environ. Sci. Pap.*, vol. 927, no. 1, pp. 1–9, 2021.
- [5] F. F. Metana, Sudarmo, and R. D. Wahyunengseh, "The Policy to Increase the Price of Fuel Oil (BBM) in 2022 Becomes a Momentum in Encouraging the Use of Electric Vehicles in Indonesia," *E3S Web Conf.*, vol. 448, no. 04003, pp. 1–4, 2023.
- [6] G. M. Jagadeesan, V. Easwaran, N. Arumugham, and S. K. Sengottaiyan, "Enhanced Solar Water Pumping Using Bifacial PV Modules with Reflective Augmentation and AI Driven Yield Prediction," *Innov. Energy Syst. Technol.*, vol. 1, no. 1, pp. 11–26, 2025.
- [7] F. A. Pamuji, H. Suryoatmojo, D. C. Riawan, Soediby, and M. Ashari, "Perancangan Sistem Pompa Air Terintegrasi On-grid Photovoltaic dan Elektrifikasi Area Persawahan guna Mengurangi Biaya Irigasi Pada Kelompok Tani " Karya Tani " Kediri , Jawa Timur," *J. Pengabd. Kpd. Masyarakat(SEWAGATI)*, vol. 8, no. 6, pp. 2357–2369, 2024.
- [8] D. Balamurali *et al.*, "A solar-powered, internet of things (IoT)-controlled water irrigation system supported by rainfall forecasts utilizing aerosols: a review," *Environ. Dev. Sustain.*, vol. 10, no. 0123456789, pp. 1–40, 2025.
- [9] I. F. Alam, A. Azis, and P. Perawati, "Perencanaan Pembangkit Listrik Tenaga Surya (PLTS) Untuk Pompa Irigasi Sawah Di Desa Ulak Aurstanding Kecamatan Pemulutan Selatan Kabupaten Ogan Ilir," *J. Surya Energy*, vol. 8, no. 1, pp. 1–11, 2023.
- [10] M. Padhiary, A. Kumar, and L. N. Sethi, "Emerging technologies for smart and sustainable precision agriculture," *Discov. Robot.*, vol. 1, no. 6, pp. 1–28, 2025.
- [11] M. I. Hamidi and Afifah, "Technical Design and Financial Feasibility Analysis of Off-Grid Photovoltaic Power Supply System for Residential Load," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 846, no. 012031, pp. 1–12, 2020.
- [12] F. R. Saputri, R. Linelson, M. Salehuddin, and D. M. Nor, "Design and development of an irrigation monitoring and control system based on BLYNK internet of things and thingspeak," *PLoS One*, vol. 20, no. 4, pp. 1–19, 2025.
- [13] A. Mdallal, A. Yasin, M. Mahmoud, M. A. Abdelkareem, A. H. Alami, and A. G. Olabi, "A comprehensive review on solar photovoltaics: Navigating generational shifts, innovations, and sustainability," *Sustain. Horizons*, vol. 13, no. 100137, pp. 1–20, 2025.
- [14] D. Rahmawati, W. Priharti, and M. I. Y. Mardiana, "A prototype of solar panel position control system based on image processing," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 830, no. 032045, pp. 1–8, 2020.
- [15] M. Španer, M. Trunti, and D. Hercog, "IoT-Based Off-Grid Solar Power Supply: Design, Implementation, and Case Study of Energy Consumption Control Using Forecasted Solar Irradiation," *Appl. Sci.*, vol. 15, no. 12018, pp. 1–28, 2025.
- [16] S. F. A. Bukhari, H. Kahveci, and M. E. Sahin, "Single Phase Induction Motor Driver for Water Pumping Powered by Photovoltaic System," *Electronics*, vol. 14, no. 1189, pp. 1–19, 2025.
- [17] Z. Anthony, E. Erhaneli, Y. Warmi, Z. Zulkarnaini, and A. Anugrah, "A new windings design

- for improving single-phase induction motor performance,” *Int. J. Electr. Comput. Eng.*, vol. 12, no. 6, pp. 5789–5798, 2022.
- [18] E. Faturiansyah, S. Syukriyadin, and H. Hafid, “Simulation Study Of A Single-Phase Induction Machine As A Water Pump System Utilizing Photovoltaic,” *J. Eng. Chain. clean Energi, Process Eng.*, vol. 2, no. 2, pp. 171–177, 2023.
- [19] S. H. Susilo and A. Setiawan, “Analysis Of The Number And Angle Of The Impeller Blade To The Performance Of Centrifugal Pump,” *EUREKA Phys. Eng.*, vol. 1, no. 5, pp. 62–68, 2021.
- [20] S. Prayitno, B. Sudjasta, and M. R. Hatuwe, “A Design of Centrifugal Pumps With 250 Liters / Second Capacity for Water Supply at Boarding School in Cibubur, Jakarta Timur,” *E3S Web Conf.*, vol. 328, no. 07017, pp. 1–5, 2021.
- [21] F. A. Syam and O. M. Arafa, “Selection process of photovoltaic standalone pumping systems,” *Sustain. Energy Res.*, vol. 10, no. 22, pp. 2–13, 2023.
- [22] M. Errouha, S. Motahhir, Q. Combe, and A. Derouich, “Intelligent control of induction motor for photovoltaic water pumping system,” *SN Appl. Sci.*, vol. 3, no. 777, pp. 1–14, 2021.
- [23] A. S. Priambodo and A. P. Nugroho, “Design & Implementation of Solar Powered Automatic Weather Station based on ESP32 and GPRS Module,” *J. Phys. Conf. Ser.*, vol. 1737, no. 012009, pp. 1–8, 2021.
- [24] P. Megantoro, S. A. Aldhama, G. S. Prihandana, and P. Vigneshwaran, “IoT-based weather station with air quality measurement using ESP32 for environmental aerial condition study,” *TELKOMNIKA Telecommun. Comput. Electron. Contro*, vol. 19, no. 4, pp. 1316–1325, 2021.
- [25] R. P. Astutik, B. Gunawan, and A. A. Mas’ud, “IoT Based Watering System Activation on Smart Garden,” *AUT J. Electr. Eng.*, vol. 10, no. 1, pp. 1–18, 2025.
- [26] C. Chang, R. Rahmad, S. Wu, C. Hsu, and P. Chung, “Enhancing flood verification using Signal Detection Theory (SDT) and IoT Sensors: A spatial scale evaluation,” *J. Hydrol.*, vol. 636, no. 131308, pp. 1–20, 2024.
- [27] R. A. Anugrah, R. R. Sika, Sunardi, and T. Marcell, “An Automatic Watering System Based on an Arduino Microcontroller and Soil Moisture Sensors with Solar Panel Power Plant,” *BIO Web Conf.*, vol. 144, no. 02003, pp. 1–12, 2024.
- [28] A. D. Saputro and M. Yantidewi, “Analysis of Air Temperature and Humidity in Kedunggalar Against BMKG Data Based on DHT11 Sensor,” *J. Phys. Conf. Ser.*, vol. 1805, no. 012045, pp. 1–9, 2021.
- [29] Y. Koch, S. Sendlbeck, M. Otto, K. Stahl, and E. Kirchner, “A review on the use of angle measurements in gear condition monitoring and fault detection,” *Mech. Syst. Signal Process.*, vol. 225, no. 112254, pp. 1–9, 2025.
- [30] A. Afandi, Khasani, Deendarlianto, I. G. N. B. Catrawedarma, and S. Wijayanta, “The development of the ultrasonic flowmeter sensors for mass flow rate measurement: A comprehensive review,” *Flow Meas. Instrum.*, vol. 97, no. 102614, pp. 1–23, 2024.
- [31] G. F. Putra, M. Fajar, H. Nauwir, and A. Pangkung, “Sistem Data Logger Pembangkit Listrik Tenaga Surya Berbasis IoT Menggunakan Sensor PZEM- 004T,” *SINERGI*, vol. 23, no. 1, pp. 93–99, 2025.
- [32] B. A. Saputra and A. Ma’arif, “Prototipe Solar Tracking Berbasis Arduino dan Sensor Light Dependent Resistor (LDR),” *Bul. Ilm. Sarj. Tek. Elektro*, vol. 4, no. 1, pp. 30–40, 2022.
- [33] M. H. Widiyanto, B. Sanjaya, V. Aurellia, and A. Chrysantathia, “Implementation Mobile Smart Farming Monitoring System With Low-Cost Platform Using BLYNK,” *J. Theor. Appl. Inf. Technol.*, vol. 100, no. 9, pp. 2723–2734, 2022.
- [34] P. S, “BLYNK 2.0 based Smart Electricity Monitoring Meter,” *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 11, no. 1, pp. 1312–1323, 2023.
- [35] J. A. Abdinoor *et al.*, “Performance of Low-Cost Air Temperature Sensors and Applied Calibration Techniques—A Systematic Review,” *Atmosphere (Basel)*, vol. 16, no. 842, pp. 1–30, 2025.