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Design and Implementation of an IoT-Based Irrigation Management System for Alternate Wetting and Drying (AWD) Technique in Rice Cultivation

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ABSTRACT

Rice irrigation management is facing considerable challenges, particularly in improving water use efficiency. This study aimed to develop an irrigation management system integrating the Alternate Wetting and Drying (AWD) technique with Internet of Things (IoT) technology. The system was constructed using ESP32 microcontroller, TOF10120 distance sensor for water level monitoring, an SD card module for data logging, 20×4 I2C LCD for real-time display, an optocoupler relay module for system control, and DS3231 real-time clock for timekeeping. Remote monitoring and control were enabled via the Blynk platform. System design was conducted using AutoCAD software, circuit simulations were performed using the Wokwi platform, and field testing was implemented in a rice cultivation area in Tabanan, Bali. Water level measurements were obtained using the TOF10120 sensor, and measurement accuracy was evaluated using MAPE (Mean Absolute Percentage Error). The system operated using a 100 WP solar panel and battery, ensuring sustainable and autonomous functionality. Results demonstrated that the IoT-based AWD irrigation management system successfully automated irrigation scheduling according to crop water requirements, achieving a high accuracy with a MAPE of 3.83%. Integration with the Blynk platform provided real-time monitoring and remote control functionalities, offering farmers an effective and user-friendly tool for optimizing irrigation water management.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a staple food source for most Asian regions and around 3.5 billion people worldwide (Li *et al*., 2018; Hashim *et al*., 2024). Indonesia is one of the countries in Asia that is highly dependent on rice plants because rice produced from processing rice grains is a staple food that is the main component of almost every basic dish of the daily diet (Susanti *et al*., 2024). Rice is a plant that requires a lot of water, but most of it is cultivated with less efficient irrigation methods (Mallareddy *et al*., 2023). Irrigation is an important means of providing and distributing sufficient water to agricultural land, including rice fields, to meet the water needs of rice plants (Tolentino *et al*., 2021). Irrigation is also an important aspect in providing, regulating, and disposing of water to support agricultural activities (Fajri, 2021).

Irrigation is important, but there are challenges faced in rice cultivation, especially related to the efficiency of water use (Tolentino *et al*., 2021). Excessive use of water resources can also lead to increased salinization and waterlogging, which will further reduce agricultural productivity (Mallareddy *et al*., 2023). Irrigation water management on rice fields in Indonesia is still carried out traditionally. In the dry season when water availability is limited, it is unable to meet all the water needs of farmer rice fields (Santoso *et al*., 2023). The habit of farmers who often use waterlogging continuously causes low efficiency of water use during the irrigation process (Taufik *et al*., 2014). If rice plants experience a shortage or excess of water supply in rice fields, the growth of rice plants can be hampered, causing crop failure (Fajri, 2021). Data released by the Ciparay Irrigation Service in 2015, stated that the impact of drought in the Wanir Irrigation Area (upstream area of the Citarum sub-DAS) was that around 1,500 hectares of rice fields in Pacet, Ciparay, and Majalaya failed to harvest (Nurseto & Nugraha, 2017).

According to Li & Barker (2004), among the various methods of irrigation water management in agricultural land such as AWD, evapotranspiration-based water scheduling (ETc), Furrow Irrigated Raised Bed (FIRB) method, aerobic rice, direct planting, and the latest Rice Intensification System (SRI), it is stated that the AWD irrigation technique shows great potential to increase water productivity in rice fields. The AWD irrigation technique is considered very promising for adoption by farmers. The application of AWD with technological support is expected to increase the efficiency of irrigation water use on agricultural land, especially in the subak system where the efficiency of irrigation water use in the vegetative phase ranges from 34–55% (Darmayasa *et al*., 2024).

In adopting AWD irrigation techniques, technological support is needed in their implementation. Technological developments encourage many people to create various types of tools that can make work easier and save time (Ridwan *et al*., 2022). Technological developments also have an impact on the agricultural sector. One example of technological developments in the agricultural sector is the existence of automation technology that can be applied in the irrigation sector. One of the automation technologies in the agricultural sector is the application of automation to the operation of IoT-based AWD irrigation techniques.

The results of research on the rice field irrigation control system using AWD irrigation techniques based on IoT technology show a system success rate in influencing the activation of water gates of 81.48%. The study recommends the use of a microcontroller with higher capabilities than the Arduino Uno, because the memory capacity used in the study has reached 60%. If the Arduino Uno is still used for further development, this can affect the stability of the program. In addition, it is recommended to use a WiFi module with higher specifications than the ESP8266 to ensure the stability of internet network communications (Husna *et al*, 2018).

Based on this, this study was conducted using the ESP32 microcontroller. The ESP32 microcontroller has higher capabilities than the Arduino Uno. The ESP32 microcontroller also has a better Wi-Fi module than the ESP8266, allowing for more stable internet communication and larger memory capacity to handle complex programs. Although this study did not include other parameters such as soil temperature and humidity which are important in rice cultivation, because the main focus in the AWD irrigation technique is water level, which treats the land as alternately flooded and unflooded (Bhandari *et al*., 2023; Lampayan, *et al*., n.d). By utilizing IoT technology, microcontrollers and proximity sensors connected to a communication platform such as Blynk, it can facilitate maintenance and reduce production costs, and allow farmers to monitor water levels in real time without the need for direct supervision on site.

This study was conducted with the aim of: (1) designing and building an automatic irrigation control system for rice plants by implementing the AWD irrigation technique using sensors; and (2) testing the performance of the automatic irrigation control system for rice plants by implementing the sensor-based AWD irrigation technique.

2. RESEARCH MATERIALS AND METHODS

The IoT-based irrigation water management system used for the application of AWD irrigation techniques on agricultural land for rice cultivation was built using an ESP32 microcontroller to control the entire process, read data from sensors, and send data via the internet to a smartphone application. The sensor functions to detect water levels, while the pump receives commands from the microcontroller to perform physical actions. The TOF10120 sensor was chosen because it has a high data reading speed and stable performance in the range of 10–50 cm, making it suitable for applications that require fast response and close-range accuracy (DroneBot Workshop, 2019). The SCC component was used to regulate battery charging from the solar panel to avoid overcharge or over discharge of the battery. The LCD functions to display important information locally or sensor data, whereas the relay is responsible for controlling pump. The SD Card module was used to store data locally as a recording log or backup. Finally, the LM2596 regulator regulates the electrical voltage from the energy source to match the working voltage requirements of the electronic components used. The ESP32 communication scheme between the water level measuring subsystem and the water pump subsystem used the Blynk platform as shown in Figure 1.

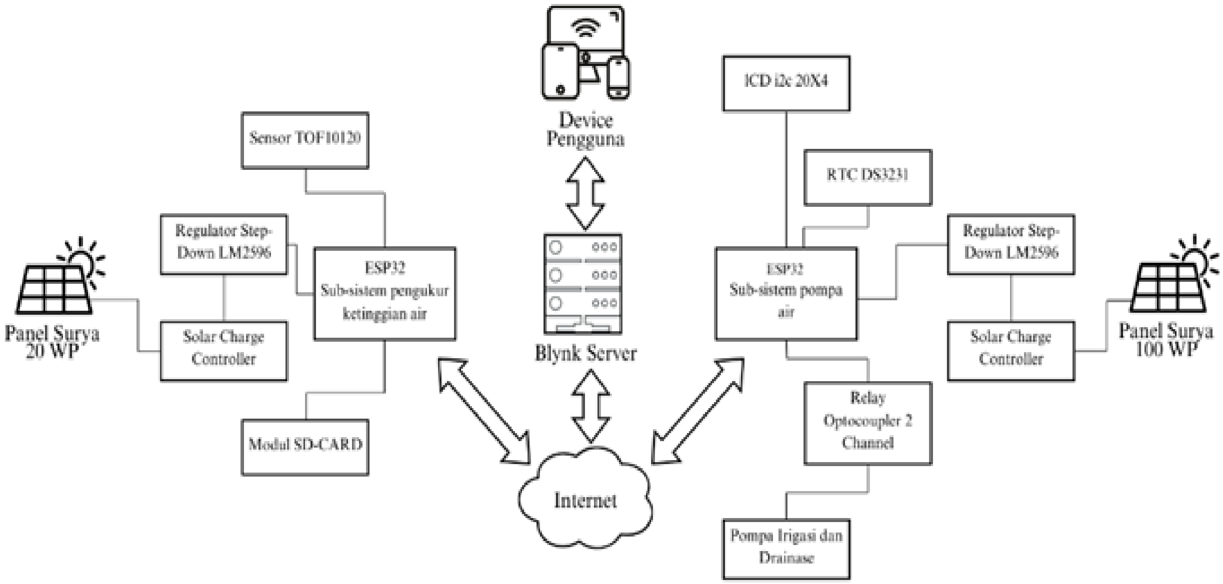

Figure 1. ESP32 communication scheme between water level measurement and water pump subsystems using Blynk platform

The research method was divided into two main aspects, namely functional testing and performance testing. Functional testing was carried out with the aim of finding out how the system works to meet the needs that have been designed, while performance testing focused on evaluating the accuracy and precision of the system in carrying out its functions, especially in measuring water levels.

2.1. Tool Functional Test

The IoT-based irrigation water management system was used for the purposes of implementing AWD irrigation techniques on agricultural land for rice cultivation, there were several main functions that must be fulfilled by the following sub-systems.

a. Water Level Measurement Subsystem

This sub-system must be able to display water level data in real-time via the Blynk platform and an LCD screen installed on the water pump control unit. Water level data was automatically stored on an SD card for documentation and further analysis.

b. Water Pump Subsystem

The sub-system controls irrigation and drainage pumps based on the age of the rice plants which is calculated in DAP (day after planting) unit. Pump control was carried out based on water level data obtained from the water level measuring sub-system. Water level settings were carried out based on several age groups as follows.

Age Group I (1–14 DAP), Inundation period: Relay 1 (irrigation pump) was active if the water level was <230 mm from the bottom of the pipe planted 200 mm deep, and Relay 2 (drainage pump) was active if the water level was >240 mm from the bottom of the pipe planted 200 mm deep (Santosa, 2023). This is because up to 14 DAP, newly transplanted plants must be in a flooded condition to minimize stress (Lampayan, *et al*., n..d.).

Age Group II (15–80 DAP), Period of application of AWD irrigation techniques: The system follows the AWD method according to the recommendations of IRRI (International Rice Research Institute) which recommends drying until the water drops 15 cm below the soil surface before being irrigated again until it reaches a puddle of 5 cm. Assuming a reference pipe of 200 mm depth, the water inundation was turned back on when the water reaches 50 mm from the bottom of the pipe (or 15 cm below the ground surface), and was stopped when the water returns to 250 mm, assuming 5 cm of water inundation (Lampayan, *et al*., n..d.).

Age Group III (81–95 DAP), Inundation period: Relay 1 was active if the water level was <240 mm from the bottom of the pipe buried 200 mm deep, and Relay 2 was active if the water level was >250 mm from the bottom of the pipe buried 200 mm deep (Santosa, 2023). This period is the flowering period, where the plants must be in a flooded condition (Lampayan, *et al*., n..d.).

2.2. Performance Test

Performance test was conducted to evaluate the accuracy and reliability of the system, especially the sensor in measuring water level. To measure the level of accuracy of the sensor measurement results, the Mean Absolute Percentage Error (MAPE) method was used. The use of the MAPE method in evaluating measurement results or forecasting aims to assess the level of prediction accuracy compared to the actual value. The MAPE value was calculated using the following equation (Barus & Ramli, 2013):

$$MAPE = \sum_{t=1}^{n} \left| \frac{y_i - \hat{y}_i}{\hat{y}_i} \right| \times 100\% \quad (1)$$

where *n* is the number of data; y_i is the observed or actual value; and $\hat{y}_i$ represents the predicted value by the sensor. The performance assessment of this system refers to the criteria set by the Mean Absolute Percentage Error (MAPE) method, which was presented in Table 1 (Puspitasari *et al*., 2022).

Table 1. Tool performance criteria based on MAPE value

MAPE Value	<10%	10-20%	20-50%	>50%
Performance Criteria	Very good	Good	Decent/Fair	Poor

2.3. Research Implementation

The research was implemented through several stages. The initial stage of the research began with the pre-design process, followed by the design of the tool using AutoCAD 2022 software. The next stage was to design a circuit schematic using the Wokwi platform, which was then integrated with a remote monitoring application using Blynk.

The design of an integration ofin irrigation water management with the AWD technique based on IoT control system with Blynk included functional and structural designs. The system consisted of two subsystems, namely the water level measuring subsystem and the water pump subsystem. Each subsystem comprised of several units, where each unit has a specific function and structure.

a. Energy generating unit in the water level measuring system was designed to provide energy supply for all electronic components that support the operation of the water level measuring system.

b. Energy generating unit in the water pump system had the same function as the energy generating unit in the water level measuring system, namely providing energy supply for all electronic components that support the operation of the water pump system.

c. Energy control unit in the water level measuring system was designed to regulate the electricity supply received from the solar panel and store it in a battery protected by a panel box. The voltage entering the battery was regulated via a solar charge controller, which was installed on the electrical panel door for easy access and adjustment.

d. Water level reader and remote monitoring unit involved some main components, such as sensors, microcontrollers, and indicator tubes with the appropriate size to be placed in the rice field area. This unit was designed to ensure accurate water level measurements and enable remote monitoring.

e. Water pump control box unit was designed to protect all electronic components placed in the outdoor environment. In addition, this unit also included the pump suitable for use in the demonstration plot.

The design results were then implemented in the component assembly stage which was integrated with the system programming stage. The next stage was to conduct functional tests and performance tests of the system being built. These stages was portrayed in the diagram shown in Figure 2.

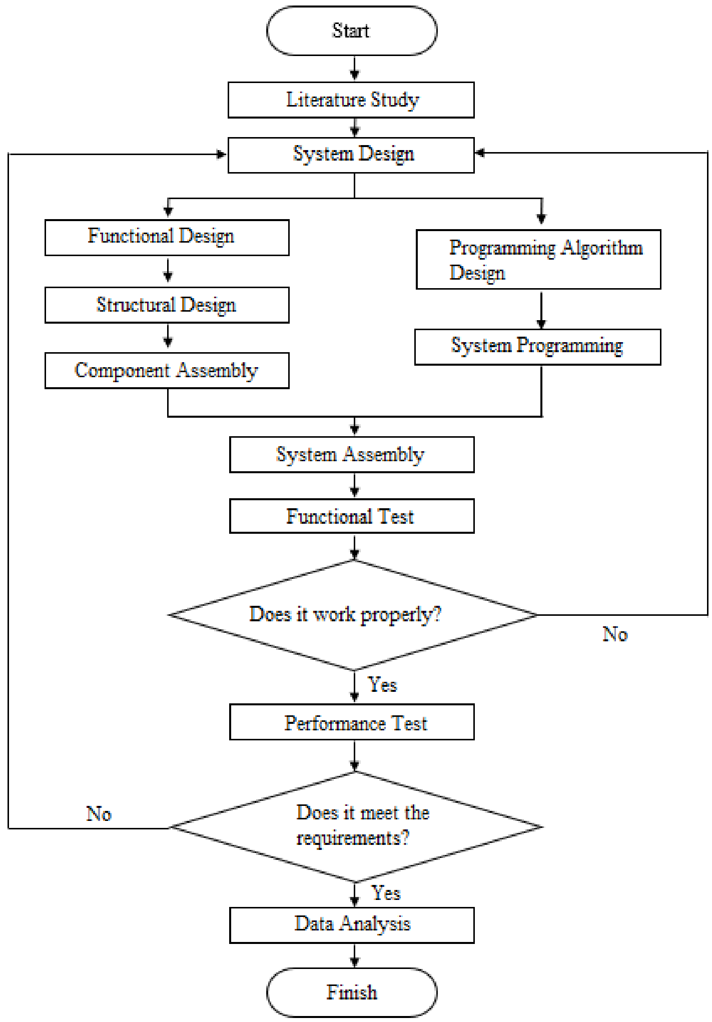

Figure 2. Research Flowchart

2.4. Design of Water Level Measurement SubSystem

This subsystem was designed to measure the water level in rice fields. This subsystem consisted of three main units, namely the energy generation unit, the energy control unit, and the water level reader unit and remote monitoring. The power supply unit used a 20 WP solar panel as the main energy source and a 7.5 Ah battery to store the energy generated. The energy was controlled by a solar charge controller located in the energy control unit. This system was supported by a 1-inch iron pipe with a height of 1.5 meters as a supporting structure. In addition, this system was equipped with a water level measuring unit made of PVC with a total height of 30 cm, consisting of 20 cm of PVC pipe as a water level indicator tube and 10 cm as a place to store electronic components. A complete visualization of this system was shown in Figure 3 and the wiring design in this system was shown in Figure 4.

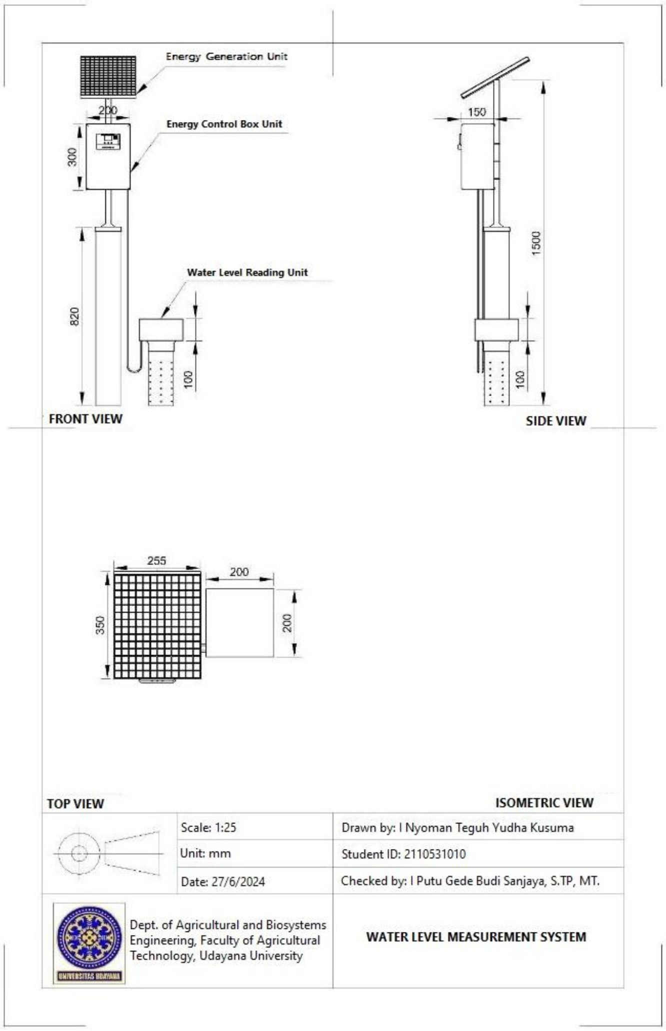

Figure 3. Design of water level measurement system

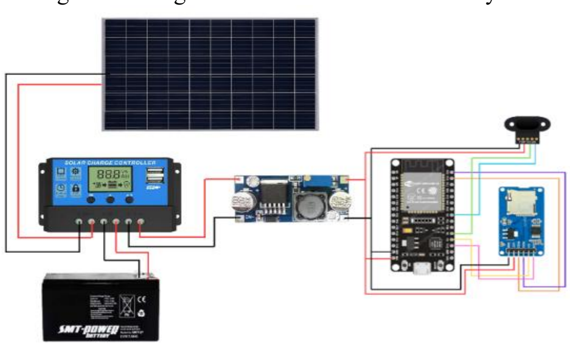

Figure 4. Wiring design on the water level measurement subsystem

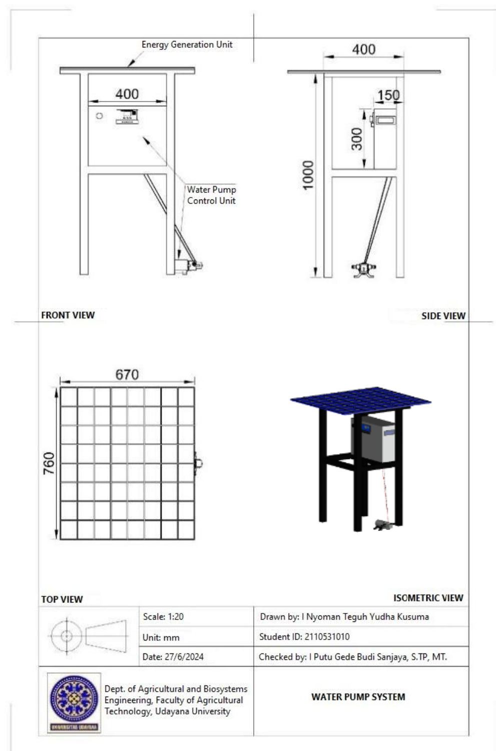

Figure 5. Design of water pump system

The schematic in Figure 4 shows an ESP32-based water level measuring system powered by solar panels. The solar panel charges the battery through the solar charge controller, then the power is reduced by the step-down module to 5V. The ESP32 reads data from the TOF sensor and time from the RTC module, then saves the data to the SD Card. Sensor calibration is not done manually in this test because the sensor used TOF10120 has been factory calibrated and has technical specifications that include accuracy and error levels. Based on the official datasheet, this sensor has an error rate of around ±5% (Sharp Corporation, n.d.). Therefore, the measurements are considered valid within acceptable tolerance limits and do not require additional calibration processes.

2.5. Water Pump Subsystem Design

This water pump subsystem was designed to automatically control irrigation and drainage pumps based on the age of the plants and the water level measured by the water level measurement system. This system consisted of a water pump control box unit that functions to protect electronic components from the weather while managing system operations based on water level data received from the sensor (Hendriyawan, 2022). Inside this control box were the main components such as ESP32, RTC, LCD, relay, and WiFi modem. This control box had dimensions of 40 cm high, 30 cm wide, and 15 cm long. In addition, this system was also equipped with a power supply unit consisting of a 100 WP solar panel and a 45 Ah battery, to supply system operating power. The entire system unit was assembled on a supporting frame that has dimensions of 1 meter high, 40 cm wide, and 47 cm long. This frame was made of hollow iron material measuring 4 cm x 4 cm. The design of the water pump system was presented in Figure 5.

The schematic in Figure 6 shows an ESP32-based water pump subsystem powered by a solar panel. Energy from the panel is stored in the battery via a solar charge controller, then reduced to 5V by a step-down module. The ESP32 controls the water pump via a relay module based on data from the water level measuring subsystem, and displays the system status on the LCD screen. Time information is obtained from the RTC module.

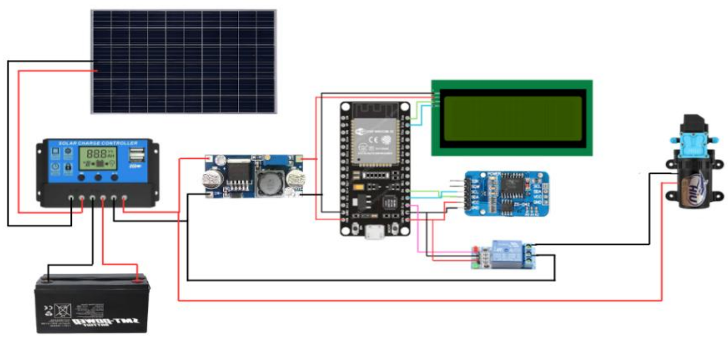

Figure 6. Wiring design on water pump subsystem

3. RESULTS AND DISCUSSION

The AWD system consists of two subsystems: a water pump subsystem and a water level measuring subsystem. The water level measuring subsystem includes an energy control unit, an energy generator, and a water level reader for remote monitoring. The energy control unit is made of iron plate with dimensions of 20 cm x 12 cm x 30 cm, protecting a 7.5 Ah battery and a solar charge controller. The energy generator is mounted on a 2-meter-high frame to support a 20 WP solar panel. The water level measuring system uses a 4-inch diameter PVC pipe and a height of 30 cm, planted 20 cm deep in the rice field to measure the water level.

In the water pump subsystem, the pump control unit measuring 30 cm x 15 cm x 40 cm is made of iron plate, protecting components such as ESP32, LCD I2C, RTC, and relay, and uses a 45 Ah VRLA battery. This unit is supported by a supporting frame with dimensions of 47 cm x 40 cm x 100 cm and is equipped with a pump with a capacity of 5 liters per minute for drainage and irrigation. The energy generator in the water pump sub-system uses a 100 WP solar panel. The design results are shown in Figures 7. The result of the error analysis is presented in Table 2.

3.1. Functional Test of Water Pump Sub-System

Functional testing of the water pump control subsystem was carried out to ensure that the sub-system can control the water pump automatically according to the water level conditions and plant age groups. This test included monitoring the I2C LCD display to verify the actual date data and water level in mm and cm units generated by the water level measuring sub-system. In addition, relay testing was carried out to ensure that the water pump works according to the control logic that has been determined based on the plant age group.

(a) (b) (c) (d)

Figure 7. (a) Water pump system, (b) Water pump system component circuit, (c) Water level measurement system, and (d) Water level measurement system component circuit

Table 2. Sensor performance effectiveness test results

Trial No.	Sensor Data (mm)	Actual Data (mm)	Absolute Percentage Error
1	76	75	1.33
2	107	107	0.00
3	126	126	0.00
4	149	144	3.47
5	155	151	2.65
6	167	164	1.83
7	175	173	1.16
8	81	81	0.00
9	95	97	2.06
10	120	118	1.69
11	134	136	1.47
12	185	185	0.00
13	199	195	2.05
14	206	202	1.98
15	229	222	3.15
16	218	213	2.35
17	233	230	1.30
18	240	240	0.00
19	253	252	0.40
20	265	263	0.76
21	273	272	0.37
22	280	283	1.06
23	69	65	6.15
24	55	57	3.51
25	42	45	6.67
26	37	36	2.78
27	25	27	7.41
28	17	11	54.55
29	92	91	1.10
30	132	127	3.94
MAPE			**3.83%**

a. I2C LCD Display Testing

This test was carried out to check whether the I2C LCD can display the actual date data and water level accurately. The water level data in mm and cm received from the water level measuring system was tested to be displayed in real-time on the LCD (Figure 8). The test results show that the I2C LCD is able to display information correctly and consistently, including updating water level data when changes occur in the system.

Figure 8. I2C LCD display when the system is turned on

b. Relay Testing Based on Age Group

Relay testing was carried out by applying different control logic according to each age group of rice plants. Each age group was tested 30 times to ensure the consistency and reliability of system operation in controlling the relay according to the designed logic. Testing was carried out using a 4-inch diameter pipe with a height of 300 mm buried 200 mm deep to measure the water level.

i) Age Group I (1–14 DAP)**:** Relay 1 was tested to be active when the water level dropped below 230 mm, and relay 2 was tested to be active when the water level exceeded 240 mm.

ii) Age Group II (15–80 DAP, AWD)**:** Only relay 1 was operational. Relay 1 was tested to be active when the water level reached 50 mm, and off when the water level reached 250 mm, according to the AWD principle.

iii) Age Group III (81–95 DAP)**:** Relay 1 is tested to be active when the water level drops below 240 mm, while relay 2 is tested to be active when the water level exceeds 250 mm.

Each relay program test for each planting age group was carried out by monitoring the system response to changes in water level simulated using sensors. This aims to ensure that the relay control logic functions according to the specifications that have been set. The results of relay testing for each planting age group are recorded automatically. The test results show that the relay function on the water pump control unit works optimally without any errors. The relay responds and operates according to the logic of the programmed conditions based on each plant age group. This proves that the water pump control unit is able to carry out irrigation and drainage functions effectively by adjusting the water level as needed at each stage of plant growth. The system response from the sensor to relay activation occurs in less than 500 milliseconds, indicating a high execution speed and is suitable for automatic irrigation applications based on the ESP32 microcontroller with a clock speed of 240 MHz.

3.2. Functional Test of Water Level Measurement System

Functional testing of the water level measurement sub-system was conducted to ensure that the system can read water level data accurately, save data to the SD card module, provide notifications according to actual conditions, and display information in real-time via the Blynk application.

i. ***Data Storage Testing on SD Card:*** The test was conducted by recording water level data measured by the TOF10120 sensor every 1 minute, then saving it to an SD card with a data format that includes the date, time, and water level value. The testing process checks whether the data is stored correctly, consistently, and can be accessed again. The test results show that the data is recorded in a structured manner and the storage is successfully stored with a storage repetition time of every 1 minute.

ii. ***Blynk Application Display Testing:*** This test was conducted to ensure that the Blynk application can display water level data in real-time. The information displayed includes water level in cm and mm (Figure 9). The test results show that data from the sensor is updated consistently.

iii. ***Notification Testing:*** Notification testing was conducted to ensure that the system can provide warnings and information that are in accordance with actual conditions and the rice plant growth phase schedule. In phase I (1–14 DAP), the system was tested to provide notifications so that the water level is maintained at 3–4 cm above the ground surface. Furthermore, in phase II (15–80 DAP) using the AWD method, notifications were tested to ensure

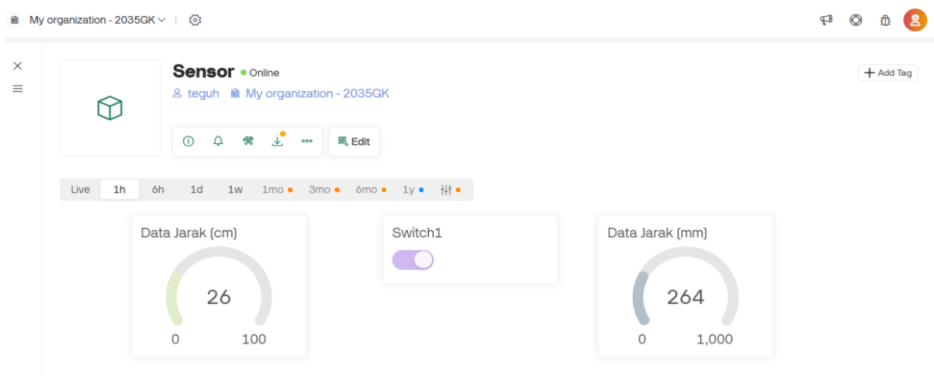

Figure 9. Blynk application display water level in cm and mm units when the unit is turned on

that the system instructs irrigation to a height of 5 cm above the ground surface when the water level drops to 15 cm below the ground surface. In phase III (81–95 DAP), notifications were tested to ensure that the water level is maintained at 4–5 cm above the ground surface. Finally, in phase IV (96 DAP until harvest), the system was tested to send notifications so that the rice fields are left dry or the maximum water level is set at 15 cm below the ground surface. The test results showed that notifications were sent in a timely manner, in accordance with actual conditions, and followed the established rice plant growth phase schedule (Figure 10).

Figure 10. Notification display on a mobile phone connected to the water level measurement system

3.3. Performance Test

The method used to assess system performance in this study is the Mean Absolute Percentage Error (MAPE). The experiment was carried out 30 times to obtain accurate data. MAPE was chosen because it can provide a clear picture of the relative error rate of the sensor measurement results compared to the actual data used as a comparison. The calculation results using the MAPE method obtained an average error value of 3.83 percent, as shown in Table 2. Based on the MAPE assessment criteria listed in Table 1, this value is included in the very good category, namely with a MAPE value of less than 10 percent. This shows that the device has a high level of accuracy and its measurement results are very reliable for practical applications (Puspitasari *et al.*, 2022). However, in the 28^{th} experiment, there was a very large reading error (APE 54.55%) because the sensor had limitations in detecting very low water levels (below

25 mm). Therefore, further research is needed to evaluate and improve the accuracy of the sensor in measuring water levels below 25 mm.

4. CONCLUSION

The IoT-based irrigation water management system in the application of AWD irrigation techniques on rice fields in this study consists of two sub-systems, namely the water level measuring sub-system and the water pump sub-system. The results of functional tests on both sub-systems indicate that the system can function properly without any errors. The design of this tool uses an ESP32 microcontroller, TOF10120 sensor, SD Card module, 20×4 I2C LCD, optocoupler relay module, RTC, and Blynk equipped with 100 and 20 WP solar panels and 45 and 7.5 Ah batteries as energy sources, and supports remote monitoring via the Blynk platform and application.

The results of the performance test show that this system successfully measures water levels with a very good level of accuracy as indicated by the average error rate obtained of 3.83% (less than 10%). This value indicates that the system is included in the very good category, meaning that the system can function well to measure water levels and send data in real time via an internet connection. However, there are some limitations in this system, including: 1) Although the system is equipped with solar panels and batteries, continuous power consumption to support devices such as ESP32, sensors, and other modules may be a problem in bad weather conditions or mismatch between energy production and power consumption. 2) The TOF10120 sensor has limitations in terms of measurement distance that can affect accuracy in certain conditions, especially in areas with object interference or other signal interference.

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