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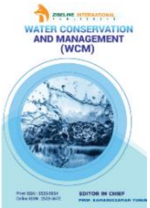

RESEARCH ARTICLE

DESIGN AND IMPLEMENTATION OF AN IOT-ENABLED CONTROL AND MONITORING SYSTEM FOR A RURAL WATER SUPPLY MICRO-PLANT

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ABSTRACT

Access to a sustainable water supply remains a critical challenge in rural areas, particularly in remote communities with limited infrastructure. This study proposes an Internet of Things (IoT) technology via microcontroller-based automation system designed to enhance the efficiency and sustainability of water supply micro-plants. The proposed system integrates a Raspberry Pi, an ADS1263 analog-to-digital converter, a water level sensor, a water pump, and an IoT platform (ThingSpeak) to monitor and control water levels of reservoir/tank in real-time. By automating pump operation based on water tank levels, the system minimizes manual intervention, ensures efficient water usage, and provides remote accessibility for monitoring. A case study conducted in Kg. Lok Dangkaan, Pitas, Malaysia, demonstrates the system's effectiveness in ensuring consistent water availability. The findings indicate that automation significantly improves operational efficiency, minimizes water wastage, and supports sustainable water management practices in rural settings. This research contributes to the development of cost-effective, scalable, and technology-driven solutions for addressing water scarcity in underserved communities with further development in the future.

KEYWORDS

Internet of Things, Raspberry Pi, Rural Water Supply, Automation, Micro-Plant

1. INTRODUCTION

Water is essential for human life, supporting various uses that create continuous demand (Hong et al., 2021). It is a fundamental element for all organisms and ecosystems. Clean drinking water is crucial for survival, and its quality significantly impacts human health and well-being (Osman et al., 2018). The human body consists of more than 60% water, and 70% of Earth's water is used for drinking, agriculture, industry, recreation, and fisheries. However, when contaminated, water harms both the environment and human health (Taru and Karwankar, 2017). The increasing water demand, driven by population growth, affects food and energy production systems (Cosgrove and Loucks, 2015). By 2050, the world will need to support an additional 2 to 2.5 billion people while also addressing energy needs for 1 billion people today. Therefore, water systems, especially in rural areas, are critical as many remote regions lack reliable water supply systems (Kisakye and Van der Bruggen, 2018). Water quality encompasses physical, biological, and chemical properties that influence organism health (Mallya and Thorarensen, 2007). While water resources are abundant, many sources, like rivers and lakes, are not directly usable due to impurities, requiring treatment systems (Laluma et al., 2019). Water Treatment Plants (WTP) process raw water using steps like coagulation, flocculation, sedimentation, filtration, and disinfection to ensure clean, drinkable water. However, manual sediment removal can be inefficient, highlighting the need for automated systems (Laluma et al., 2019). For remote areas, mobile, autonomous WTPs with remote monitoring capabilities are essential (García et al., 2018).

Water storage tanks need to be refilled when levels drop, but users may forget to turn off the pump, causing overflow (Shevale et al., 2018). Water wastage also occurs due to leaks in domestic and industrial systems (Kulkarni et al., 2020). Monitoring water levels in storage tanks necessitates the use of automated systems to effectively prevent overflow and ensure optimal water usage (Jan et al., 2022). And traditional water quality monitoring involves manual sample collection and lab testing, which is time-consuming, labor-intensive, and costly (Hakimi and Jamil, 2021). These methods are less efficient and prone to human error, delaying corrective actions (Duy et al., 2015). Thus, an IoT-based automatic monitoring system for real-time water treatment optimization is necessary (Doni et al., 2018 ; Othman et al., 2020). Previous development for this site included a Hardware-in-the-Loop (HIL) simulation to validate the control unit before field deployment, ensuring reliable operation in the absence of a physical prototype (Miskon et al., 2024).

IoT connects devices, machines, and humans in real-time using advanced technologies (Wang et al., 2021). It enables smart interactions through sensors, communication, microcontrollers, actuators, and user interfaces, enhancing the quality of life (Wu et al., 2020). IoT is applied in various fields like smart homes, healthcare, and tracking systems (Xia et al., 2012). Advancements in microelectronics and wireless communication have led to the development of WSNs, which consist of sensor nodes that work

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together to collect specific data and transmit it to a central station (Kupwade Patil and Chen, 2013). WSNs are widely used for environmental monitoring, data collection, and analysis in remote areas (Sipani et al., 2018).

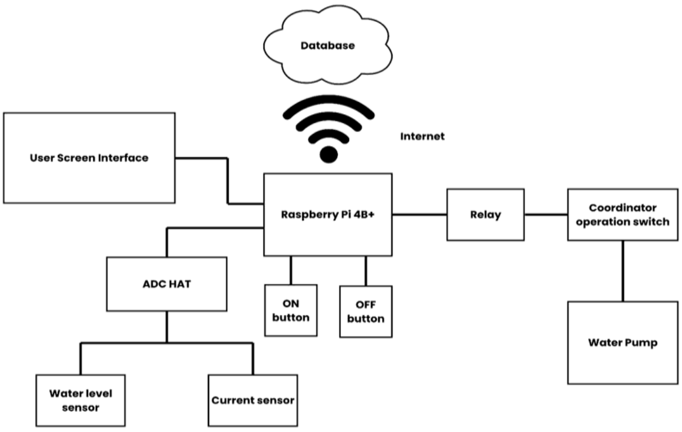


Figure 1 : The diagram block picture for the proposed system design.

Hence, the research proposes the following objectives:

- To develop an automated and integrated operating system based on a microcontroller that will improve the efficiency of clean water production and electricity consumption based on time-based logic conditions for a micro water supply plant.
- To measure, survey, and analyze the condition of key parameters of the micro water supply plant, such as water level.
- To develop an Internet of Things (IoT)-based operational monitoring system for monitoring micro water supply plant in rural areas.

2. METHODOLOGY

The following outlines the fundamental principles of a systematic tracking device, based on the essential components needed for designing the proposed device to control and monitoring micro-plants water distribution:

- High precision data acquisition: The ADS1263, an ultra-high-resolution 32-bit analog-to-digital converter (ADC), offering 10 analog input channels and integrated programmable gain amplifiers and digital filters. It is selected for its ability to deliver precise, low-noise measurements, making it ideal for scientific applications. The ADS1263 communicates with the Raspberry Pi via SPI, enabling real-time data acquisition, logging, and cloud integration. Its performance is exemplified in a case study where "the high resolution of the ADS1263 enabled the detection of small changes in sensor outputs over time (Knapp and Bloom, 2022).
- Integration of sensors: Rapid advancement of microelectromechanical systems and wireless communication technology has driven the development of Wireless Sensor Networks (WSNs) consist of interconnected nodes that collaboratively detect and collect specific data based on their designated functions (Kupwade Patil and Chen, 2013).
- User-Friendly Interface: Minimalistic design significantly enhances operator engagement in micro-plant operations by improving navigation and visual appeal. A streamlined interface reduces cognitive load, guiding users efficiently toward their goals with minimal effort. This simplicity increases user satisfaction, aiding locals in rural areas with minimal effort (Maddirala, 2019).
- Efficient power management: Reducing energy consumption and water waste while ensuring efficient water distribution (Rathod et al., 2023).
- Online monitoring: The local database supports remote monitoring, data retrieval, and trend analysis, while ThingSpeak cloud services store data online for analytics processing (Balasubramaniyan and Manivannan, 2016).
- Operator-friendly design: The system incorporates both automatic and manual control modes, selectable via an operator switch. It features a graphical user interface (GUI) for real-time monitoring, along with a simple button-based logic sequence that facilitates comprehensive and intuitive control. Additionally, a safety emergency shutdown button is integrated to allow immediate system deactivation in critical situations, enhancing operational safety.

Fig. 1. presents the proposed system, which adheres to the fundamental principles outlined. The Raspberry Pi serves as the central controller, acquiring data from the ultrasonic water level sensor and CT sensor via Analog-to-Digital Converter (ADC) HAT. Since both sensors generate analog voltage outputs, the ADC HAT converts these signals into digital codes, enabling the Raspberry Pi to process the data with high accuracy and precision. A simplified Graphical User Interface (GUI) is developed to provide real-time monitoring of water levels and pump activation status for the micro-plant operator.

The system operates in three distinct modes, determined by the operational switch coordinator. In automatic mode (A), the Raspberry Pi evaluates water level conditions and predefined activation times to systematically control the water pump via relay signals. In manual mode (M), the operator manually controls the pump using ON and OFF buttons. In off mode (O), all pump activations are disabled, ensuring complete system shutdown when required.

During the tool's design, software support is implemented to control and manage system components through programming. The process flow algorithm, illustrated in Figure 2, operates as follows:

- The ultrasonic water level sensor and CT sensor acquire real-time water level data and check the water pump activation status.
- The collected data is displayed to the operator and transmitted to ThingSpeak for both physical and online remote monitoring.
- In automatic mode (A), if the water level and designated time conditions are met, the system activates the water pump for distribution.
- In manual mode (M), the operator manually controls the pump activation for distribution.
- In off mode (O), all pump activations are disabled.

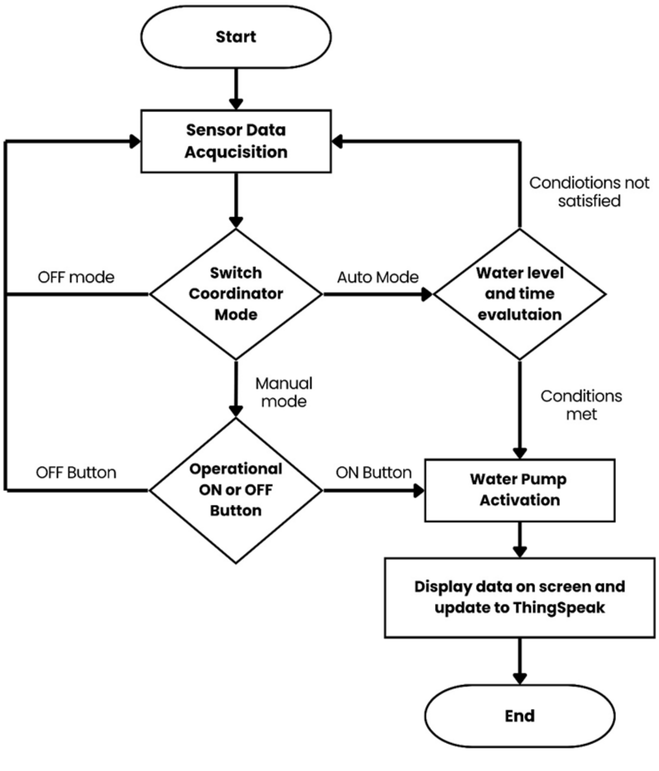


Figure 2 : Flowchart for the proposed research.

This algorithm provides a structured, step-by-step process that manages the operation of the water pump control system, ensuring efficient management and seamless integration of its components. The installation diagram serves as a comprehensive representation of the system's final implementation, detailing the interconnections and functionalities of each component. It illustrates how the Raspberry Pi-based controller, along with sensors and relays, collaborates to regulate water distribution in an automated and manual manner.

By following the designed specifications, the system is prepared for deployment, ensuring accurate real-time monitoring, automated decision-making, and secure operation. The installation diagram plays a crucial role in guiding micro-plant operators in setting up and maintaining the system efficiently, contributing to a reliable and sustainable water management solution. Fig. 3 illustrates the installation diagram for the Raspberry Pi-based water pump control system, detailing the interconnections among key components. This system is designed for real-time water level monitoring, automated pump control, and remote data accessibility, making it a robust solution for sustainable water management.

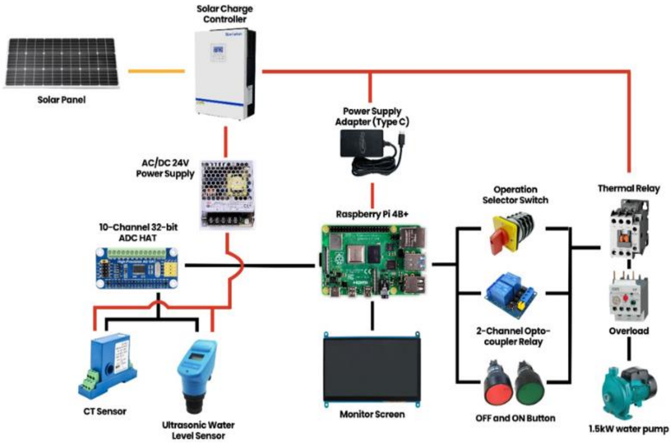


Figure 3 : The wiring diagram for the proposed design.

The Rasperry Pi 4B+, functioning as the central processing unit, acquires sensor data from the ultrasonic water level sensor and CT sensor through a 10-channel Analog-to-Digital Converter (ADC) HAT. Since both sensors output analog signals, the ADC HAT converts these signals into digital data, enabling precise processing. The acquired data is displayed on a user screen interface, allowing the micro-plant operator to monitor real-time water levels and pump activation status. Additionally, the system transmits the data to ThingSpeak cloud services, enabling online remote monitoring and analytics for performance evaluation.

The system operates based on a three-mode operational switch coordinator, which determines how the water pump functions explained in table 1:

Table 1: System operation based on switch coordinator mode

Mode	System Operation
A (Automatic)	Raspberry Pi systematically evaluates water level readings from the sensor and determines whether the pump should be activated. Once the designated water level conditions and time constraints are met, the system automatically sends control signals to the dual optocoupler relay, which then activates the water pump. This mode ensures autonomous water distribution without manual intervention, optimizing efficiency.
M (Manual)	The operator has direct control over the pump through physical ON and OFF buttons. Unlike the automatic mode, this setting does not rely on water level conditions, allowing the user to activate or deactivate the pump as needed.
O (Off)	The system completely disables the pump operation, preventing any activation. This is useful during maintenance or when water distribution is not required.

For safety and reliability, the dual optocoupler relay acts as an intermediary control unit between the Raspberry Pi and the thermal relay and overload protection unit. The OMRON and thermal relay provide protection against overheating and excessive current, while the overload unit ensures that the 1.5 kW water pump operates within safe electrical limits. These protective components safeguard the system from potential electrical faults, enhancing durability and operational safety.

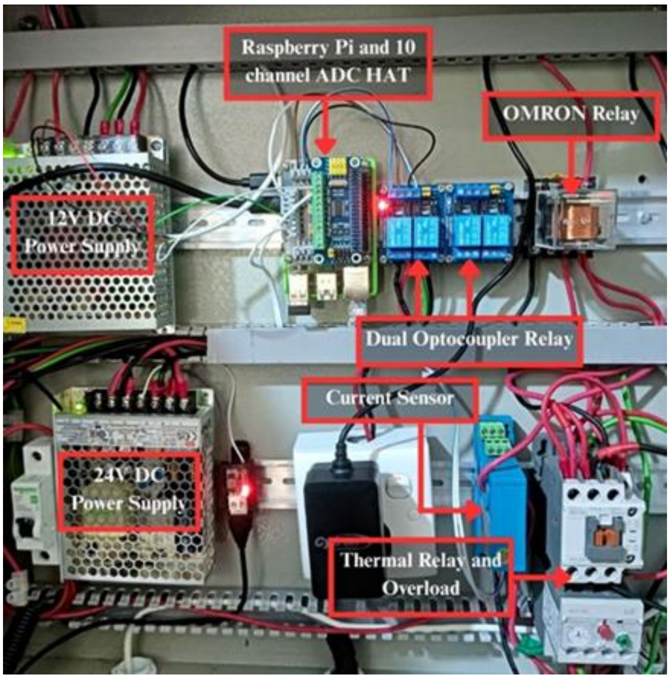
By integrating digital control, real-time monitoring, and cloud-based analytics, this system provides a comprehensive solution for efficient and automated water resource management. The installation diagram visually represents the wiring connections, ensuring clear guidance for assembly and implementation. Proper installation and calibration of the components will maximize system performance, improving water distribution efficiency in rural micro-plant applications.

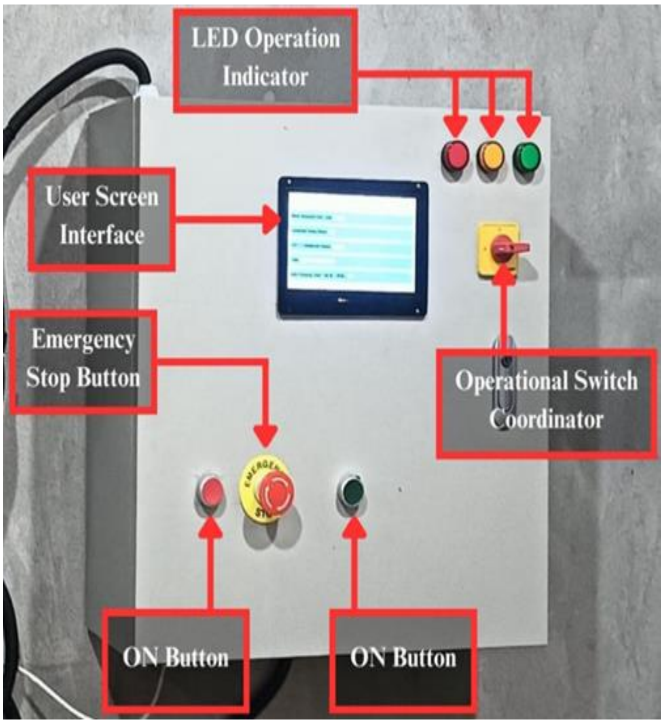
System development and installation at site

The hardware implementation for this study involved the integration of water level ultrasonic sensor and 1.5 kW water pump modules into an automated system to establish a functional IoT-enabled monitoring and controlling micro-plant. The hardware components were systematically assembled in a metal-casing for housing.

Extra precautions are added to safely wire all electrical arrangements between low-power devices such as the Raspberry Pi and high-power devices such as the water pump. Upon successful integration, the system enabled real-time water level and water pump operation monitoring, including remote access with online control.

Fig. 4(a) presents the internal assembly of the system, highlighting key components and their installation layout. For optimal performance and safety, it is strongly recommended that installation be performed by qualified personnel with expertise in electronics, as improper handling may lead to electrical interference or pose safety risks. The system integrates two AC/DC power supply converters of 12 V and 24 V designed to meet the specific power requirements of various components.





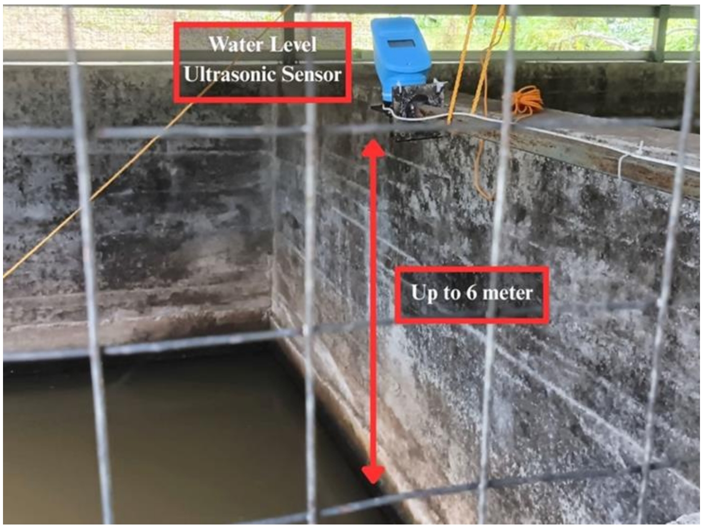


Figure 4 : System installation: (a) Internal hardware components and connection, (b) External hardware components and connection, (c) Water level ultrasonic sensor installation.

Fig. 4(b) shows the external assembly of the system, including additional components. An emergency stop button is incorporated to immediately disable the system by cutting off the power supply, ensuring user safety during critical situations. To enhance manual user interaction and system monitoring, a set of tri-color LED indicators (red, yellow, and green) has been installed. These indicators provide real-time feedback on the system's operational state, as summarized in Table 2.

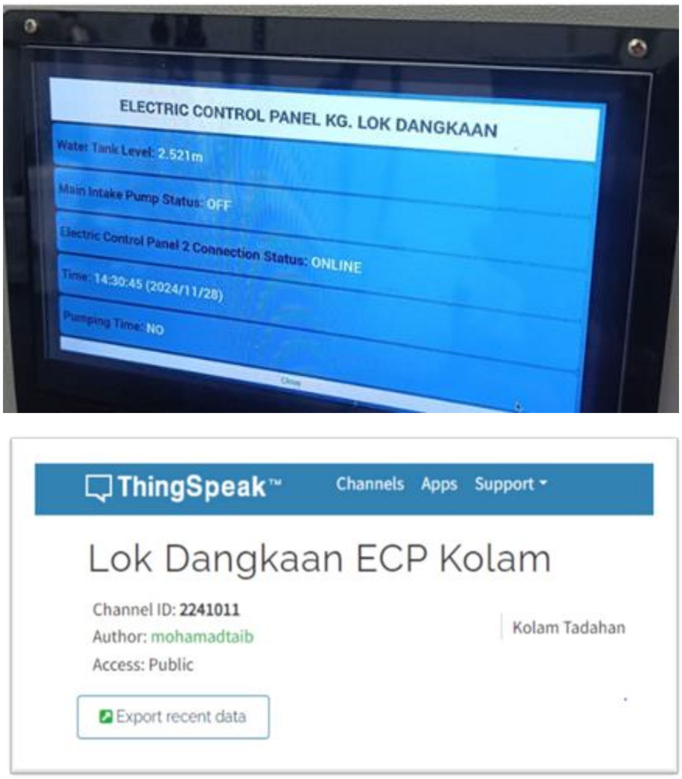
Table 2: System operation based on switch coordinator mode

LED Color	System Operation
Red	The water pump is currently operating.
Yellow	The system is functioning autonomously based on programmed evaluations.
Green	The system is under manual control by the micro-plant operator.

Meanwhile, Fig 4(c) presents the ultrasonic water level sensor is mounted above the water surface, with a vertical measurement range of 6 meters from the sensor to the bottom of the water reservoir.

3. DATA COLLECTION

The recorded data includes water level measurements, obtained through real-time monitoring of fluctuations within the water reservoir, and water pump activation, detected via current sensing to ensure the pump operates at appropriate water levels and durations. Fig. 5(a) presents the data visualized through a user interface simplified designed for the micro-plant operator and other users.



ELECTRIC CONTROL PANEL KG. LOK DANGKAAN
Water Tank Level: 2.521m
Main Intake Pump Status: OFF
Electric Control Panel 2 Connection Status: ONLINE
Time: 14:30:45 (2024/11/28)
Pumping Time: NO

ThingSpeak™ Channels Apps Support
Lok Dangkaan ECP Kolam
Channel ID: 2241011
Author: mohamadtaib
Access: Public
Kolam Tadahan
Export recent data

Figure 5 : Real-time monitoring: (a) Highlighted data presented to micro-plant operator and (b) Real-time data is sent to ThingSpeak for remote online monitoring.

Fig. 5(b) also transmitted to an online database, ThingSpeak, as outlined in the proposed methodology.

The data collected on the ThingSpeak online database for water level and water pump current are summarized in Table 3 and Table 4. The conversion calculations are expected as follows:

$$\text{Water level height (m)} = \left(\frac{\text{Voltage output 1}}{\text{Maximum Voltage Output}}\right) \times \text{Maximum sensor capability}$$

$$\text{Water level height (m)} = \frac{\text{V1}}{\text{5V}} \times \text{6m}$$

$$\text{Pump Activation Indicator [Current (A)]} = \frac{\text{Voltage output 2}}{\text{Maximum Voltage Output}} \times \text{Maximum sensor capability}$$

$$\text{Current (A)} = \frac{\text{V2}}{\text{5V}} \times \text{50A}$$

Table 3: The data collected using the proposed system in automatic mode using ThingSpeak

Time	Water level in voltage (DC)	Water level	Condition	Water pump current in voltage (DC)	Water pump current	State
10:10 a.m.	1.1683V	1.4019m	Sufficient	0.0799V	0.799A	ON
10:11 a.m.	1.1679V	1.4015m	Sufficient	0.0791V	0.791A	ON
10:12 a.m.	1.1677V	1.4012m	Sufficient	0.0778V	0.778A	ON
10:13 a.m.	1.1675V	1.4010m	Sufficient	0.0774V	0.774A	ON
10:14 a.m.	1.1674V	1.4009m	Sufficient	0.0774V	0.774A	ON
10:15 a.m.	1.1673V	1.4007m	Sufficient	0.7513V	0.751A	ON
10:16 a.m.	1.1671V	1.4005m	Sufficient	0.0785V	0.784A	ON
10:17 a.m	1.1668V	1.4002m	Sufficient	0.0799V	0.799A	ON

Table 3 (cont): The data collected using the proposed system in automatic mode using ThingSpeak

10:18 a.m.	1.1666V	1.3999m	Insufficient	0.0020V	0.020A	OFF
10:20 a.m.	1.1665V	1.3998m	Insufficient	0.0025V	0.025A	OFF
10:21 a.m.	1.1665V	1.3998m	Insufficient	0.0020V	0.020A	OFF
10:22 a.m.	1.1664V	1.3997m	Insufficient	0.0019V	0.019A	OFF
10:23 a.m.	1.1665V	1.3998m	Insufficient	0.0091V	0.019A	OFF
10:24 a.m.	1.1665V	1.3998m	Insufficient	0.0018V	0.018A	OFF
10:25 a.m.	1.1664V	1.3997m	Insufficient	0.0024V	0.024A	OFF
10:26 a.m.	1.1665V	1.3998m	Insufficient	0.0021V	0.021A	OFF
-	-	-	-	-	-	-
13:55 p.m.	1.3288V	1.5945m	Sufficient	0.0792V	0.792A	ON
13:56 p.m.	1.3287V	1.5944m	Sufficient	0.0774V	0.774A	ON
13:57 p.m.	1.3285V	1.5942m	Sufficient	0.0783V	0.783A	ON
13:58 p.m.	1.3284V	1.5941m	Sufficient	0.0785V	0.785A	ON
13:59 p.m.	1.3281V	1.5938m	Sufficient	0.0794V	0.794A	ON
14:00 p.m.	1.3281V	1.5938m	Sufficient	0.0024V	0.024A	OFF
14:00 p.m.	1.3281V	1.5938m	Sufficient	0.0025V	0.025A	OFF
14:01 p.m.	1.3281V	1.5938m	Sufficient	0.0025V	0.025A	OFF
14:02 p.m.	1.3280V	1.5937m	Sufficient	0.0024V	0.024A	OFF
14:03 p.m.	1.3281V	1.5938m	Sufficient	0.0024V	0.024A	OFF
14:04 p.m.	1.3281V	1.5938m	Sufficient	0.0020V	0.020A	OFF

4. DISCUSSION

Based on the data presented in Table 3, the water level and water pump current reading demonstrate insignificant reading difference and accurate reading within expected value. Whereas water level data are decreasing gradually and current reading from the water pump fluctuates within expected value. The water pump will automatically activate when the water level is above 1.40 meters and to determine the activation threshold is above

These observations indicate that the proposed system functions reliably in automatic mode. When the water level is sufficient specifically at or above 1.400 meters, the system identifies this condition and activates the water pump, as reflected by the ON state and a corresponding increase in pump current. Conversely, when the water level falls below the 1.4000-meter threshold, the system classifies the condition as insufficient, resulting in the pump being switched OFF to prevent unnecessary operation.

This threshold of 1.400 meters was selected based on experimental calibration to ensure efficient pump usage and to maintain an adequate water supply. The consistent pump responses to changes around this threshold indicate that the control logic is effectively integrated into the monitoring system. Furthermore, the current drawn by the pump while in the ON state remains within an expected operational range (approximately 0.783 A to 0.799 A), confirming stable performance under sufficient water levels. Meanwhile, in the OFF state, the current drops significantly (to approximately 0.018 A to 0.025 A), verifying the pump's deactivation.

Overall, the automatic switching of the water pump based on the defined threshold enhances the system's operational efficiency and reliability, making it suitable for sustainable water supply applications especially in rural areas, to ensure efficient electricity usage and to prolong the durability of the water pump when water levels are low or entirely absent to avoid fatal premature failure.

Based on the data presented starting from 14:00 p.m., the current readings drop sharply to 0.024 A or lower, confirming proper deactivation and energy conservation. The water level during the OFF state remains above the predefined threshold (1.400 m), suggesting the system retained the pump in the OFF state due to fulfilment of time-based logic conditions, further confirming that the system doesn't over-pump even at sufficient levels, optimizing energy use.

This additional data set reinforces the accuracy, stability, and energy efficiency of the control logic implemented in the IoT-based water pump system. It also validates the threshold-based operation and responsiveness of the system across continuous time intervals.

5. CONCLUSION

The development and implementation of an IoT-enabled microcontroller-based control and monitoring system for a rural water supply micro-plant has proven effective in improving water resource management in underserved areas. The integration of a Raspberry Pi, ADS1263 ADC, and ThingSpeak cloud platform allowed for precise real-time monitoring, automatic pump operation, and remote access to system data. The system successfully reduces manual intervention, optimizes energy usage, and prolongs the lifespan of hardware components through threshold-based automation. For future improvements, the system can be enhanced by integrating water quality sensors, such as pH, turbidity, and conductivity sensors. This would allow the system to not only monitor water levels but also ensure the water's safety and compliance with health standards. The implementation of predictive analytics or AI-based control algorithms could also help forecast water usage patterns and automate system responses more intelligently. Furthermore, SMS or mobile app notifications can be integrated to alert local operators about abnormal water levels, pump faults, or sensor failures. Adding data logging features on SD cards for offline access and fail-safe redundancy mechanisms would also increase reliability. Overall, the system demonstrates scalability and adaptability, making it suitable for widespread deployment in various rural contexts. With further refinements, this solution holds great potential for contributing toward sustainable development goals and enhancing the quality of life in remote communities.

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