Development of a Solar-Powered Multi Parameter Water Quality Monitoring Prototype with Integrated Battery Monitoring for Smart Agriculture

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Abstract

The objective of this study was to design and implement a prototype for an automated water quality monitoring system integrated with a solar powered charging unit, a filtration system and battery status monitoring. The system incorporates a multi parameter sensor array and an energy monitoring module controlled by an ESP32 microcontroller, enabling real time data acquisition and transmission to a customized web dashboard for immediate analysis. Experimental results demonstrated high measurement reliability with sensor accuracy rates of 88.43% for potential of hydrogen (pH) and 95.54% for electrical conductivity (EC). The results also showed that all measured water quality parameters after treatment by the prototype were significantly improved compared with those of untreated water ($p \leq 0.05$). Specifically, treated water showed increased pH and reduced turbidity, EC and total dissolved solids (TDS) indicating its suitability for agricultural applications.

Keywords: Smart agriculture, Solar powered monitoring, Water quality sensors, Battery analytics, ESP32

1. Introduction

Water resource management and water quality control are fundamental factors affecting the sustainability of agricultural production systems. In the era of Smart farming, the focus has shifted toward using real time numerical data to control water quality and plan water usage for maximum efficiency [1]. In the context of smart farming, effective water quality control and water resource planning rely on the monitoring of several key parameters, including pH level, EC, TDS, turbidity and water temperature [1-2]. The pH value represents the hydrogen ion concentration in water, serving as a critical indicator that influences nutrient availability and biological processes in agricultural systems [3]. Deviations in pH from the optimal range can lead to nutrient deficiencies or heavy metal toxicity in plants. Additionally, TDS and EC serve as indicators of mineral ion concentration in water. Excessive EC levels can inhibit photosynthesis and reduce osmotic potential in plant roots [4]. Furthermore, turbidity serves as a physical indicator of water

clarity. High levels of suspended solids not only lead to the clogging of emitters in irrigation systems but also diminish the efficiency of natural uv disinfection processes in water [5].

When considering water quality monitoring systems, conventional approaches have historically relied on field sampling for laboratory analysis or manual measurements using handheld devices. Traditional water quality monitoring, typically conducted once or twice weekly [1], results in a data gap of up to 164 hours per week (based on 168 hours/week minus approximately 4 hours per sampling event), which is insufficient for precise decision making. Consequently, the application of Internet of Things (IoT) technology, integrated with smart sensor networks, has emerged as a primary strategy for enhancing agricultural infrastructure [6]. This approach enables measurements at intervals of 1–15 minutes while maintaining a lower error rate than conventional methods [7]. Furthermore, traditional agriculture often faces power instability, as most cultivated areas are located off grid, far from the main electrical infrastructure. Relying on the grid involves high installation costs and risks of voltage drops, which can potentially damage microcontroller circuits that are sensitive to milliampere level fluctuations [4]. Solar energy integration emerged as the most viable alternative for remote areas. However, solar energy is an intermittent source [8]. Therefore, incorporating battery monitoring, to display real time voltage and remaining capacity, is crucial. This data empowers farmers to effectively manage both the system's energy consumption and the overall water management for agricultural operations.

Accordingly, this research designed an integrated solar powered multi parameter water quality monitoring system capable of real-time data visualization. This prototype improved upon earlier designs, limited to pH and TDS monitoring, by incorporating battery monitoring, EC and turbidity sensors. By utilizing a high performance microcontroller to process and transmit multi parameter quality data and energy status to a custom developed web dashboard, farmers can remotely monitor water conditions via mobile devices. This system serves as a crucial decision support tool, preventing excessive water consumption and supporting sustainable water management in off grid areas with limited technical personnel.

2. Objective

2.1 Design and construction of an automated multi parameter water quality monitoring prototype integrated with a solar-powered charging system, a water filtration unit and a battery monitoring system controlled by an ESP32 microcontroller and IoT for real time visualization.

2.2 Evaluation of the functional performance of the monitoring prototype by conducting a comparative analysis of water quality parameters before and after the filtration and monitoring process.

3. Methodology

3.1 Design and construction of the multi parameter automated water quality monitoring prototype with solar charging and battery analytics

3.1.1 Structural design and solar power system installation. The overall system and components were designed using SolidWorks (CAD) software. The primary frame was constructed from 20×20 mm aluminum profiles, with 5 mm thick acrylic sheets serving as mounting plates for the various components.

A 20 W solar panel was installed at an inclination angle at 15–20° to align with the site's latitude for optimal irradiance. The power subsystem consisted of a solar charge controller integrated with a 12V, 10Ah Sealed Lead-Acid (SLA) battery. A stepdown converter (buck converter) was utilized to regulate the battery voltage to the required level for the microcontroller unit. Furthermore, the multi-stage filtration system was installed to filter the water before entering the water quality monitor. The filtration system consisted of synthetic fibers, volcanic rock and filter media balls to enhance water quality.

3.1.2 Sensor systems, hardware and software Integration. The system integrates sensors for monitoring pH, TDS, turbidity and EC via the analog-to-digital converter (ADC) ports of the ESP32 microcontroller. A flow rate sensor and a battery monitoring module connected to the solar charging system were linked to interrupt pins to enable pulse-count-based calculations. The flow rate sensor was calibrated and measured at approximately 4,000 ml/min. To ensure system safety and prevent electrical interference, a relay module was employed to galvanically isolate the water pump's power circuit from the control logic. Regarding data management, the firmware was developed to support Wi-Fi connectivity, enabling the transmission of multi parameter sensor data to a customized real time web dashboard.

3.2 Evaluation of the prototype performance through water quality measurement before and after passing through the automated multi parameter water quality monitoring prototype with solar charging system and battery power status monitoring system

3.2.1 The operational testing of the prototype was conducted by comparing sensor readings against certified laboratory standard solutions. The percentage of error (% Error) and accuracy (% accuracy) was calculated to quantify the precision of the instrumentation. The analysis methodology was conducted in accordance with [9] using the following formulas

$$\% \text{ Error } = [\text{Vm} - \text{Vt}]/\text{Vt x}100 \quad (1)$$

$$\% \text{ Accuracy } = 100 - \%\text{Error} \quad (2)$$

where Vm represents the value measured by the prototype and Vt denotes the reference standard.

3.2.2 Physico-chemical analysis of water quality from various sources before and after the multi parameter automated water quality monitoring prototype with solar charging and battery analytics treatment

3.2.2.1 Potential of hydrogen (pH) was measured in water samples at 25°C using a Mettler S220 pH meter.

3.2.2.2 Turbidity was analyzed indirectly by measuring light absorbance at 400 nm using a Shimadzu UV-1800 UV-Visible spectrophotometer following APHA Method 5910 [10]. Data interpretation relied on the principle that the measured absorbance value is directly proportional to the turbidity level within the water sample.

3.2.2.3 Total dissolved solids (TDS) measurement using a field based TDS Pen. Low TDS levels represent water quality near that of pure water.

3.2.2.4 Electrical conductivity (EC) measurement using a field based sensor with a BNC-type conductivity electrode (60 cm cable length), where EC levels Indicated soluble impurities and lower values signified higher water purity

Comparative analysis was performed on water samples collected before and after filtration processing through the automated water quality monitoring prototype integrated with a solar charging system. These water sources were specifically selected to represent the primary water supplies utilized by farmers in Thailand. While irrigation canals serve as the mainstream agricultural water source, natural ponds and fish ponds were chosen as representative water supplies commonly found in remote areas that are heavily relied upon for farming activities. The experimental design utilized a Paired-Samples T-test approach, conducted with five independent replicates to ensure statistical consistency. Statistical data analysis was executed using SPSS to determine significant differences at a confidence level of 95%.

4. Results and Discussion

4.1 Results of the design and construction of the automated multi parameter water quality monitoring prototype with solar charging system and battery power status monitoring system

The design and operational testing of the developed prototype are illustrated in Figures 1–4, while the comprehensive validation of system accuracy is summarized in Tables 1 and 2. Data acquired from the pH, TDS, EC and turbidity sensors were processed and transmitted via an ESP32 microcontroller to a web application (web dashboard) for real time monitoring. By integrating a solar cell system with a battery monitoring system, the system could therefore operate continuously in off grid agricultural areas. This allowed farmers to ensure that the backup energy is sufficient to power the sensors and the wireless communication system 24 hours a day, even under low light conditions.

Experimental results demonstrated that the prototype was capable of simultaneous water quality detection and real time battery status visualization. In terms of measurement accuracy, the pH sensor exhibited a percentage error of 11.57%, corresponding to an accuracy rate of 88.43%. Meanwhile, the EC sensor showed a significantly lower error rate of 4.46%, achieving a high measurement accuracy of 95.54%. The high measurement accuracy achieved by the EC and pH sensor can be attributed to several factors. First, the sensor utilized was a calibrated commercial-grade device equipped with built-in automatic temperature compensation (ATC), which minimized the thermal drift that commonly affects electrical conductivity readings. Second, the evaluation was conducted under controlled laboratory conditions using certified standard reference solutions. This eliminated external environmental interferences, such as suspended solids and temperature fluctuations, thereby ensuring highly stable and reproducible measurements.

Based on the load analysis and energy budget analysis of the system (data not shown), it was found that the estimated energy consumption of the control unit, sensors and water pump (operating 30 min/day) over 24 hours totaled 96 Wh. The system's battery backup capacity provides a total of 120 Wh. At a safe depth of discharge (DoD) of 50%, this capacity is sufficient to sustain prototype operation for 24 hours. Furthermore, the real time battery status display enables farmers to manage both water quality monitoring

and agricultural water usage effectively. [11] reported that IoT based monitoring systems powered by solar energy have been demonstrated to ensure continuous sensor operation in remote agricultural areas.

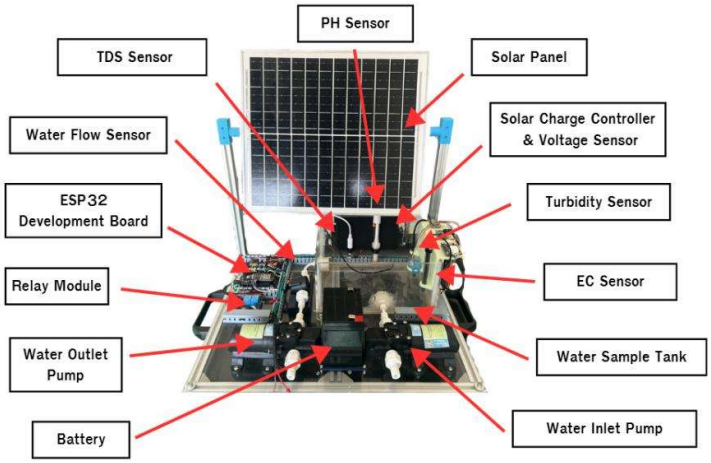


Figure 1 Multi parameter automated water quality monitoring prototype with integrated solar charging system and battery analytics.

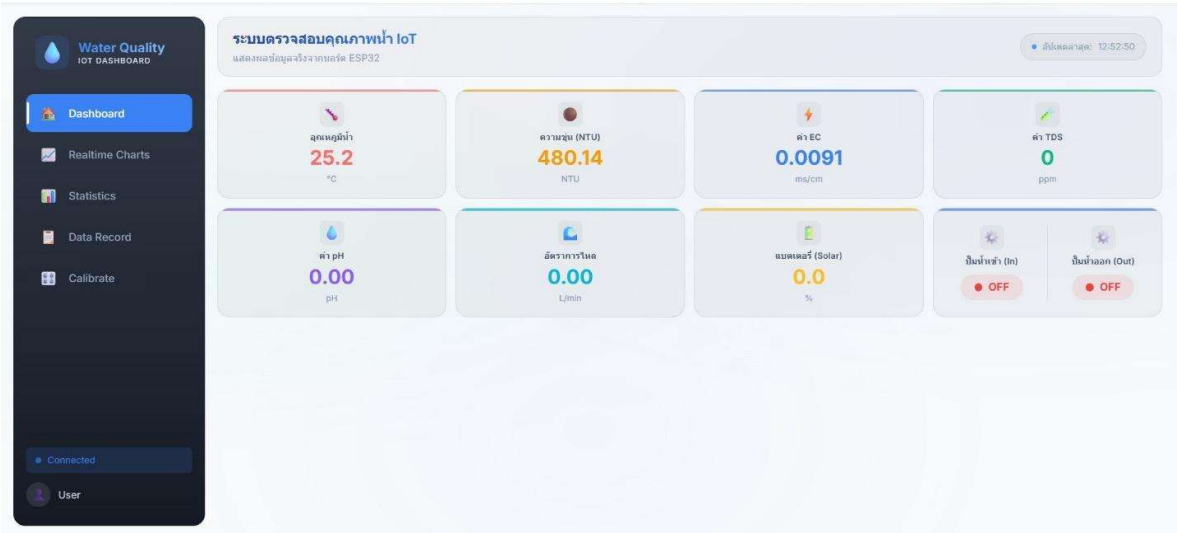


Figure 2 Web-based dashboard interface for the multi parameter automated water quality monitoring prototype with integrated solar charging data and real-time battery analytics.

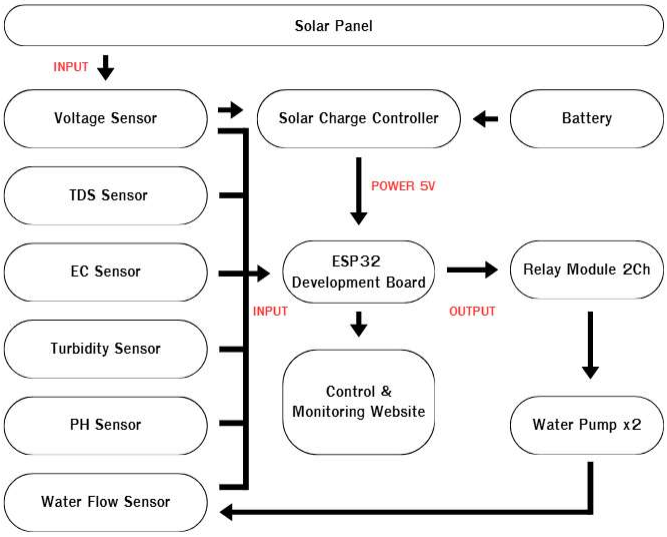


Figure 3 Signal flow of the multi parameter automated water quality monitoring prototype with integrated solar charging and battery analytics systems.

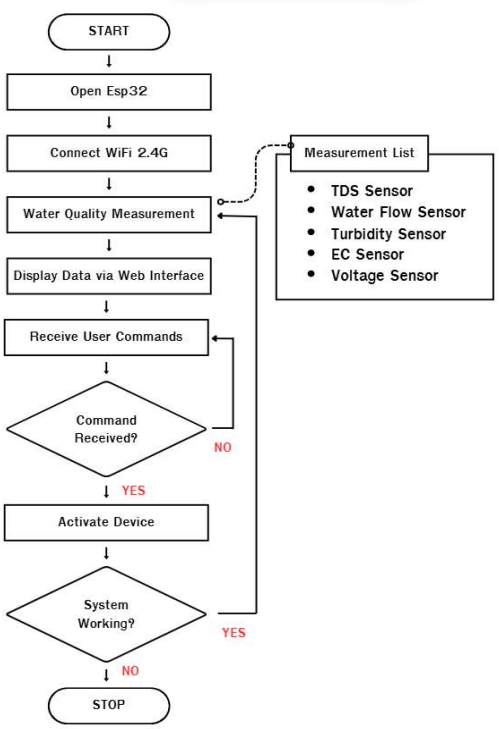


Figure 4 Operational flowchart of the multi parameter automated water quality monitoring prototype with integrated solar charging and battery analytics systems.

Table 1 Measurement accuracy of the pH sensor compared against a standard buffer solution at pH 7.0.

Quality	Prototype	Standard buffer solution.	% error	% accuracy
pH	7.81±0.58	7	11.57	88.43

Table 2 Measurement accuracy of the Electrical Conductivity (EC) sensor compared against a standard calibration solution at 1,413 μS/cm.

Quality	Prototype	Standard calibration solution	% error	% accuracy
EC (μS/cm)	1350±42	1,413	4.46	95.54

4.2 Evaluation of the prototype performance through water quality measurement before and after passing through the automated multi parameter water quality monitoring prototype with solar charging system and battery power status monitoring system

Performance evaluation of the automated monitoring prototype was conducted by analyzing water quality in multi parameters before and after treatment presented in Table 3 and Figure 5. The results indicated that the multi parameter water quality monitoring system prototype effectively improved the water quality from three types of water sources (irrigation canals, natural ponds and fish ponds). The turbidity of water from various sources decreased significantly ($p \leq 0.05$). This may be attributed to the filtration components, consisting of synthetic fibers, volcanic rock and filter media balls, which functioned to trap suspended particles in the water. Furthermore, volcanic rock, which exhibited alkaline properties, facilitated the adsorption of acidic organic compounds and CO_2, contributing to the observed increase in pH from 7.49 to 8.91, irrigation canals (8.51 to 8.91), natural ponds (7.52 to 7.86), and fish ponds (7.49 to 7.73). Meanwhile, for irrigation canals, TDS decreased from 218.17 to 163.78 mg/l and EC from 400 to 217 μS/cm. For natural ponds, TDS decreased from 748.12 to 452.35 mg/l and EC from 1,009 to 613 μS/cm. For fish ponds, TDS decreased from 791.32 to 700.50 mg/l and EC from 1,126 to 1,005 μS/cm. The reduction in TDS and turbidity helped decrease damage to the piping system and prevented clogging of related equipment [5,12]. Thus, the water treated by this prototype possessed suitable quality for agricultural applications.

Table 3 pH, TDS, Turbidity and EC values of water from various sources, before and after treatment processing through the multi parameter automated water quality monitoring prototype with integrated solar charging and battery analytics

Quality		Irrigation canals	Natural ponds	Fish ponds
pH	before	8.51^{b}±0.02	7.52^{b}±0.15	7.49^{b}±0.12
	after	8.91^{a}±0.04	7.86^{a}±0.01	7.73^{a}±0.03
TDS	before	218.17^{a}±1.23	748.12^{a}±5.52	791.32^{a}±9.18
(mg/l)	after	163.78^{b}±13.12	452.35^{b}±16.40	700.50^{b}±3.14
Turbidity	before	0.02^{a}±0.001	0.08^{a}±0.01	1.15^{a}±0.01
	after	0.01^{b}±0.01	0.05^{b}±0.001	0.84^{b}±0.001
EC (μS/cm)	before	400^{a}±21.01	$1,009^{a}$±67.52	$1,126^{a}$±54.62
	after	217^{b}±10.03	613^{b}±45.23	$1,005^{b}$±52.78

Superscripts ^{a,b} within the same column in the same parameter indicate significant differences ($p \leq 0.05$)



a b c d e f

Figure 5 Visual comparison of water samples from irrigation canal, natural pond and fish pond before (a, b, and c, respectively) and after (d, e, and f, respectively) treatment via the multi parameter automated water quality monitoring prototype with integrated solar charging and battery analytics.

5. Conclusion

The development of the multi parameter automated water quality monitoring prototype, integrated with a solar charging system and battery analytics, was designed to provide real time visualization of flow rates and multi variable water quality parameters. Developed specifically for off grid agricultural applications, the system incorporates a battery monitoring system to ensure continuous operation without reliance on the main electrical grid. Performance testing demonstrated that the prototype achieves a measurement accuracy of 88.43–95.54%. Furthermore, the treated water from three water sources- irrigation canal, natural pond and fish pond-showed significant quality improvements compared to pre-treatment samples, reaching levels suitable for agricultural use. In conclusion, this prototype offers a technological solution for remote water management by enabling precise, real time monitoring and improving water purity. The system reduces the risk of crop damage, optimizes water resource efficiency in remote areas, and enhances agricultural competitiveness by supporting precise and sustainable water management.

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