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IDENTIFICATION OF pH SENSOR SENSITIVITY LEVELS ACROSS VARIOUS AQUATIC ECOSYSTEMS BASED ON DIRECT MEASUREMENT WITH WIRELESS DATA COMMUNICATION

Identifikasi Tingkat Sensitivitas Sensor pH Pada Berbagai Ekosistem Perairan Berbasis Pengukuran Langsung Dengan Komunikasi Data Nirkabel

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ABSTRACT

Characterizing sensor sensitivity across various aquatic ecosystems is essential for determining the sensor's ability to accurately detect pH changes under real-world field conditions. Given this context, this study aims to assess the sensitivity of a capacitive pH sensor in several aquatic ecosystems through in situ measurements. This study utilized several water samples for direct calibration and testing. Four water samples with known pH levels were used for calibration. For the subsequent testing phase, water samples were collected from the following ecosystems: ecosystem 1 (river), ecosystem 2 (rice field), ecosystem 3 (estuary), ecosystem 4 (sea), and ecosystem 5 (fish pond). The system was built using an Arduino MEGA+ESP8266 microcontroller. Regarding the sensor component, a pH sensor (DF-Robot) with an analog signal output was employed. The calibrated system was examined using five different water ecosystems. The results show that the system was calibrated, with a span of 6.47-7.50. The sensitivity levels depend on the ecosystem conditions (0.08 V/pH level). The findings are expected to provide a scientific basis for developing more reliable pH sensors and to support sustainable water quality monitoring and mitigation efforts.

Keywords: Data communication, Internet of Things, Monitoring system, pH level, Water

ABSTRAK

Menentukan karakteristik sensitivitas sensor di berbagai ekosistem perairan sangat penting untuk mengetahui kemampuan sensor dalam mendeteksi perubahan pH secara akurat dalam kondisi lapangan yang sebenarnya. Dalam konteks ini, penelitian ini bertujuan untuk mengevaluasi sensitivitas sensor pH kapasitif pada beberapa ekosistem perairan melalui pengukuran *in situ*. Penelitian ini menggunakan beberapa sampel air untuk kalibrasi dan pengujian secara langsung. Empat sampel air dengan tingkat pH yang telah diketahui digunakan untuk proses kalibrasi. Untuk tahap pengujian selanjutnya, sampel air diambil dari ekosistem berikut: ekosistem 1 (sungai), ekosistem 2 (sawah), ekosistem 3 (muara), ekosistem 4 (laut), dan ekosistem 5 (kolam ikan). Sistem ini dibangun menggunakan mikrokontroler Arduino MEGA+ESP8266. Terkait komponen sensor, digunakan sensor pH (DF-Robot) dengan keluaran sinyal analog. Sistem yang telah dikalibrasi tersebut diuji menggunakan lima ekosistem perairan yang berbeda. Hasil penelitian menunjukkan bahwa sistem telah berhasil dikalibrasi dengan rentang nilai 6,47–7,50. Tingkat sensitivitas bergantung pada kondisi ekosistem (0,08 V/tingkat pH). Temuan ini diharapkan dapat memberikan landasan ilmiah bagi pengembangan sensor pH yang lebih andal serta mendukung upaya pemantauan kualitas air dan mitigasi berkelanjutan.

Kata kunci: Komunikasi data, Internet of Things, Sistem pemantauan, Tingkat pH, Air

INTRODUCTION

Aquatic ecosystems encompass various environments—such as swamps, rivers, lakes, estuaries, coastal areas, and the open ocean—each with distinct physical, chemical, and biological characteristics (Wang, 2024). This diversity of characteristics shapes ecological functions that play a vital role in maintaining environmental balance while supporting the lives of various aquatic organisms (Clance et al., 2023). Each type of aquatic ecosystem provides distinct environmental services, ranging from habitat provision and carbon storage to the supply of water resources for human needs. This diversity of conditions means that each aquatic ecosystem requires a water quality monitoring approach tailored to its specific environmental characteristics (Serra et al., 2023).

Water quality in any aquatic ecosystem is influenced by various natural factors and human activities occurring in the surrounding area (Maskooni et al., 2024). Natural factors include geological conditions, rainfall, temperature, and biogeochemical processes, whereas anthropogenic activities—such as agriculture, industry, settlements, and waste disposal—can alter the characteristics of water bodies (Kaplan et al., 2024). Differences in the influence of these factors result in varying water quality conditions across ecosystems—conditions that can even fluctuate over time and across space. Therefore, accurate water quality monitoring is a crucial step toward maintaining the functional sustainability of aquatic ecosystems and supporting effective water resource management (Ngwenya et al., 2025).

The pH parameter is a key indicator for assessing water quality in various aquatic ecosystems (Moeinzadeh et al., 2024). The pH value indicates the acidity or alkalinity of water, which influences chemical reactions, nutrient availability, metal solubility, and the survival of aquatic organisms (Sajib et al., 2025). Changes in pH levels outside the optimum range can disrupt ecosystem balance and degrade the quality of the aquatic environment. Therefore, accurate pH measurement is a crucial component of water quality monitoring, serving as a basis for decision-making in aquatic environmental management (Farouk et al., 2023).

Sensor technology determines the accuracy and reliability of pH measurements across various aquatic environmental conditions (Sakthivelpathi et al., 2024). Various types of sensors have been developed—including optical, resistive, electrochemical, and capacitive sensors, as well as hybrid technologies—each with distinct operating principles, sensitivities, and measurement characteristics (Gregorio et al., 2024). These differing characteristics mean that each sensor technology possesses specific advantages and limitations when used in diverse aquatic ecosystem conditions. Therefore, selecting the appropriate sensor technology is crucial for obtaining accurate, stable, and reliable pH data during in situ measurements (Ren et al., 2024). Studies on the characteristics of capacitive pH sensors across various aquatic ecosystems remain very limited, particularly in identifying sensor sensitivity through in situ measurements. Most previous research has focused on sensor material development, accuracy improvements, or laboratory-based testing; consequently, comprehensive information on how sensor responses change under varying aquatic conditions is not yet available (Gregorio et al., 2024; Sakthivelpathi et al., 2024). On the other hand, characterizing sensor sensitivity across various aquatic ecosystems is essential for determining the sensor's ability to accurately detect pH changes under real-world field conditions. Given this context, this study aims to assess the sensitivity of a capacitive pH sensor in several aquatic ecosystems through in situ measurements. The findings are expected to provide a scientific basis for developing more reliable pH sensors and to support sustainable water quality monitoring and mitigation efforts.

MATERIALS AND METHODS

Water Samples

This study utilized several water samples for direct calibration and testing. Four water samples with known pH levels were used for calibration. For the subsequent testing phase, water samples were collected from the following ecosystems: ecosystem 1 (river), ecosystem 2 (rice field), ecosystem 3 (estuary), ecosystem 4 (sea), and ecosystem 5 (fish pond) (Alaydrus et al., 2025).

System Design

The system was built using an Arduino MEGA+ESP8266 microcontroller. It was connected to a modem for wireless data communication (via the ThingSpeak.com portal) (Akhyar et al., 2025; Anggriani et al., 2024). This IoT portal was used to collect data remotely. A display was used to show data from calibrated sensor readings. Regarding the sensor component, a pH sensor (DF-Robot) with an analog signal output was employed. The sensor's output pin was connected to an analog pin on the microcontroller (Figure 1) (Budianto et al., 2025). This pin will produce a voltage (V) reading, which was subsequently converted into a pH value during the calibration stage.

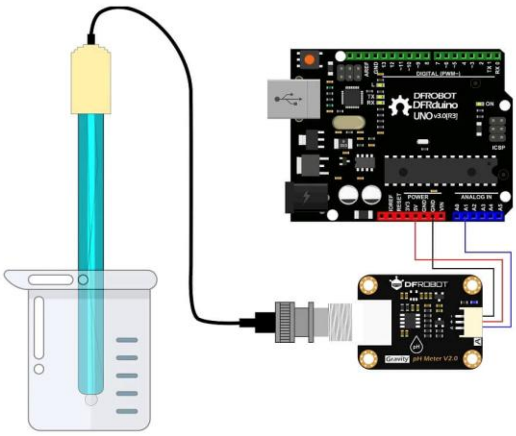

Figure 1. System Design (source: dfrobot.com, 2026)

For data communication purposes, a website interface was designed on the ThingSpeak.com portal, featuring several channels to display measurement results. Values read by the system are transmitted to the ThingSpeak.com portal using the platform's provided API key (Application Programming Interface). A "write" API key is embedded in the Arduino IDE code via Serial3 communication (115200), while sensor data is sent to the display via Serial1 communication (9600). The IoT process utilizes a 5-6-7 switch configuration on the microcontroller with TX3, whereas the analog process employs a 3-4 switch configuration with TX0.

Calibration

The system was calibrated using water samples with known pH values (determined via a reference device/comparator). The sensor probe is placed inside the measurement chamber—without touching the chamber floor—for the duration of the measurement. The water sample is introduced into the chamber. After a 60–90-second interval, the sensor's output voltage is recorded. Simultaneously, the pH value from the reference device is noted as the y-value.

System Examination

The calibrated system was examined using five different water ecosystems. These examinations were conducted using multipoint measurements on site (*in situ*). The received data were recorded in the ThingSpeak.com portal. The data communication was examined using RSSI (Received Signal Strength Indicator), connection latency, and packet loss parameters.

Statistical Analysis

All data were interpreted as the mean and standard deviation ($n = 3$). A t-test was used to analyze differences between groups, with $p < 0.05$ considered significant (all data analyses were conducted using Microsoft Excel).

RESULTS

Calibration Results

The results of the calibration process are presented in Table 1. These values were obtained by measuring four types of water samples with known pH levels using a reference instrument. Each data point represents the average of three repeated measurements. The data indicate that the water samples exhibited varying pH values. These differences are reflected in the varying voltage outputs from the pH sensor (analog values converted to voltage), which ranged from 0.53 V to 0.59 V. The response time required to achieve the most stable reading ranged from 60 to 90 seconds.

Table 1. Calibration results using a comparator device

Water Samples	Voltages	pH Levels
Sample 1	0.53 V	6.47
Sample 2	0.57 V	7.20
Sample 3	0.56 V	7.00
Sample 4	0.59 V	7.50

All measurements were conducted inside an experimental chamber: temperature = 25-26 °C

Further analysis reveals that the data exhibit a relatively linear relationship. According to the table above, the sensor's output voltage is linearly related to the pH level. Consequently, the calibration process involves generating a linear curve plotting voltage (x-axis) against pH level (y-axis) (Figure 2), resulting in the following equation ($R^2 = 0.998$) (Eq. 1). This equation was then inserted into the source code (Arduino IDE):

$$y = 17.32x - 2.7 \quad (1)$$

y represents the calibrated pH value, while *x* represents the sensor voltage ($R^2 > 0.90$).

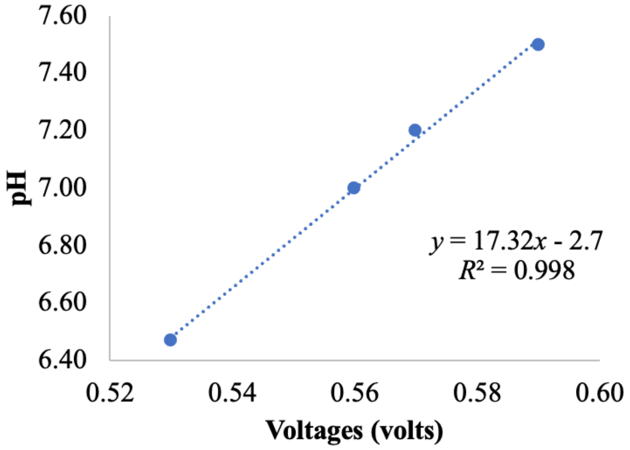

Figure 2. Calibration Result Using a Linear Approach

Examination Results

Following successful calibration, the next step involved testing the sensor system using various water samples obtained from different aquatic ecosystems (five locations). This testing was conducted in situ, with the designed system transported to the test sites. The sensor probe was placed directly into an open, flowing water system after a 60-second stabilization period. The test results are presented in Table 2. This procedure was repeated three times to obtain the pH values.

Table 2. Examination results with a multipoint measurement method

Water Samples	pH-System	pH-Comparator
Ecosystem 1 (river)	7.32	7.09
Ecosystem 2 (rice field)	7.57	7.20
Ecosystem 3 (estuary)	8.73	8.68
Ecosystem 4 (sea)	8.39	8.49
Ecosystem 5 (fish pond)	7.32	7.35

All measurements were conducted in situ: temperature = 31-33 °C

The results of this field testing process were obtained through multipoint measurements, with three repetitions per test and comparison with a reference instrument. This comparison aimed to determine the sensor's accuracy in measuring pH across various aquatic ecosystems and to establish its measurement range. Further analysis revealed that the sensor system's accuracy ranged from 94.9% to 99.4%. For ecosystem sample 1, the accuracy was 96.7 %, indicating a slight discrepancy relative to the reference system. Similar results were observed for ecosystems 3 and 4, with accuracy levels of 99.4 % and 98.8 %, respectively. Overall, the calculated average accuracy was 98%.

Wireless Data Communication Examination

The final test involved analyzing data transmission efficiency via IoT. This process used an internet connection and a modem, which were activated during data acquisition. Data readings captured by the sensor system (within the Arduino IDE application) were compared against readings from the ThingSpeak.com portal. The initial analysis involved comparing RSSI values recorded during data transmission; these results are expressed in dBm. The test results showed an average ping time of 62–92 ms. RSSI values ranged from -62 to -61 dBm, with FSPL (Free Space Path Loss) values between 43.57 and 46.06 dB.

DISCUSSION

Each aquatic ecosystem has a distinct pH, influenced by geological characteristics, mineral composition, and the physical, chemical, and biological processes occurring within it. Rock weathering, organismal photosynthesis and respiration, and the decomposition of organic matter drive changes in hydrogen ion concentrations, directly affecting the water's acidity or alkalinity. Furthermore, inputs such as rainfall, river flow, seawater intrusion, and anthropogenic activities—including agriculture and waste disposal—contribute to pH variations across different aquatic ecosystems. These factors fluctuate over time with seasonal and climatic changes and vary spatially across regions. Consequently, ecosystems such as swamps, rivers, lakes, estuaries, coastal areas, and oceans generally exhibit different pH ranges tailored to their specific environmental conditions. Such pH variations demonstrate that each ecosystem possesses unique water chemistry characteristics, necessitating appropriate measurement approaches to ensure accurate results (Chemeri et al., 2025).

Each aquatic ecosystem possesses distinct physical and chemical characteristics—such as electrical conductivity (EC), total dissolved solids (TDS), salinity, dissolved oxygen (DO), and temperature—as they are influenced by water sources, mineral content, geological conditions, and human activities (Misman et al., 2023). Differences in dissolved ion concentrations—reflected in EC and TDS values—can affect the water's ionic balance, thereby contributing to changes in pH. Furthermore, variations in temperature and salinity influence chemical reaction rates and compound solubility, thereby affecting the water's acidity or alkalinity. The interaction of these parameters results in distinct water quality characteristics for each ecosystem, even when they are in close geographic proximity (Moeinzadeh et al., 2024). Therefore, pH measurement should take into account other water quality parameters so as to more accurately represent aquatic conditions (Syeed et al., 2023).

Capacitive-based pH sensors exhibit high sensitivity to changes in the dielectric properties of the sensor material's surface caused by variations in hydrogen ion concentration within a solution. These characteristics enable the sensor to deliver a rapid, stable response with good measurement resolution across a wide pH range, including in high-pH aquatic environments. Furthermore, capacitive sensors have low power consumption, making them suitable for in-situ water quality monitoring systems. Consequently, capacitive sensors offer a promising, effective alternative for pH measurement across diverse aquatic ecosystems (Ren et al., 2024).

Sensor stability is a major challenge in "in situ" measurements because sensors must operate continuously under dynamic environmental conditions. Fluctuations in temperature, salinity, humidity, and water chemical composition, as well as fouling, can cause signal drift, thereby reducing measurement accuracy. Furthermore, prolonged environmental exposure can alter sensor material characteristics, leading to a decline in sensitivity. Consequently, testing sensor stability across various aquatic ecosystem conditions is essential to ensure the reliability of direct pH measurements (Farouk et al., 2023).

CONCLUSION

A pH sensor (DF-Robot) with an analog signal output was employed in this research. The calibrated system was examined using five different water ecosystems. The results show that the system was calibrated, with a span of 6.47-7.50. The sensitivity levels depend on the ecosystem conditions (0.08 V/pH level). The findings are expected to provide a scientific basis for developing more reliable pH sensors and to support sustainable water quality monitoring and mitigation efforts.

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