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Research Article

Comparative Analysis of Salinity Readings for Water Quality Monitoring between IoT-Based Sensor Systems and Refractometer

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A B S T R A C T

Salinity is among the factors that affect aquaculture water quality, along with pH, temperature, dissolved oxygen (DO), and ammonia. Osmotic pressure is influenced by salinity, which directly affects the aquatic biota. Osmotic pressure increases with increasing salinity in the body of water. The threshold salinity varies between aquatic biotas. If there is an isosmotic pressure, the aquatic biota will thrive. Specific gravity, electrical conductivity (EC), light refraction, and chlorine titration are commonly used in salinity tests. Refractometer light refraction and water quality monitoring (WQM) salinity sensor EC were the salinity measurements employed in this research. In general, difficulties experienced while employing EC measurements to the tool's accuracy and precision. The salinity sensor was evaluated and verified in this research by comparing the findings of WQM readings with a refractometer over a three-day term. The sensors of 22 WQM devices were tested and validated in 22 BLUPPB (Balai Layanan Usaha Produksi Perikanan Budidaya, Aquaculture Production Business Service Center) ponds. The WQM was put in the center of the pond, and salinity was measured with a refractometer at four spots around the pond's edge. On the first trial, the WQM error and accuracy values were 19.90% and 80.10%, respectively; on the second trial, they were 9.58% and 90.42%, and on the third attempt, they were 16.21% and 83.79%. WQM accuracy was 0.7128, 0.7285, and 0.7174 on the first, second, and third time

1. INTRODUCTION

Water quality is one of the crucial factors determining the success of fish farming. Water quality that meets the needs of the fish can support their survival and growth [1] [2]. One of the key factors influencing water quality is salinity. Salinity can affect the biological processes of aquatic organisms and directly influence their life, such as growth rate, feed conversion, and survival [3]. This is because salinity affects the osmotic pressure in the body fluids of aquatic organisms. If the osmotic pressure exceeds the organism’s tolerance threshold, more energy is required to maintain the body's osmotic balance through the process of osmo-regulation.

Salinity measurement can be conducted using several methods, including chlorine titration, specific gravity, light refraction, and electrical conductivity [4]. However, the most commonly used methods in the field are light refraction and electrical conductivity (EC).

The salinity measurement method based on light refraction uses an instrument called a refractometer. Light refraction occurs in a refractometer when light passes through two media with different densities, resulting in a refractive indeks [5]. Seawater behaves as an optical medium, where its refractive index is intrinsically linked to its density. Given that density varies with salinity and temperature and that refractive index is wavelength-dependent, measuring seawater’s refractive index enables determination of absolute salinity [6]. This method is advantageous because it is

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easy to use, offers fairly high accuracy, and is relatively inexpensive. However, the drawback is that it cannot be used for real-time measurements, thus requiring periodic measurements. One method that allows real-time measurement is using electrical conductivity.

Electrical conductivity (EC) is a salinity measurement method based on the principle of redox (reduction-oxidation) [7]. Two or four electrodes are placed in a solution, and a potential difference is applied. This method can be carried out digitally by means of the Internet of Things (IoT), allowing real-time measurement of salinity values via a microcontroller or single-board computer such as an ESP32, ESP8266, or Raspberry Pi. However, the drawback of this method is the need for calibration to achieve high accuracy and precision [8].

Studies on IoT-based salinity measurement approach have attracted considerable attention from researchers due to its simplicity, real-time results, and relatively low cost. However, accuracy remains a key consideration, especially in aquaculture settings where environmental variability can affect sensor performance. Jais et al. [9] developed a low-cost IoT-based water quality monitoring system for Asian seabass aquaculture that incorporates analog EC sensors to measure salinity. The authors reported that the EC sensors were calibrated against a refractometer to establish a correlation between EC readings and salinity, yielding an accuracy of ±0.29 ppt. To maintain this level of accuracy, the authors recommended regular monthly calibration of the sensors. While the study did not explicitly explore factors such as temperature drift or sensor degradation, the emphasis on calibration suggests an awareness of the conditions affecting measurement reliability. Le Menn & Nair highlight that salinity measurements based on electrical conductivity (EC) sensors are significantly affected by external variables such as temperature and osmosis pressure, leading to measurement drift and necessitating careful calibration [10]. They also emphasize that EC-based methods cannot directly measure absolute salinity (i.e., the total mass of dissolved salts in seawater), as they are limited to estimating practical salinity (a unitless value derived from electrical conductivity, temperature, and pressure using empirical formulas). Moreover, Gu et al. [6] noted that the linear correlation between EC and salinity is often not universally applicable, particularly in systems with complex ionic dynamics such as brackish water ponds. Therefore, although EC-based approaches offer efficiency and seamless integration within IoT systems, comparison with reference methods such as refractometers becomes crucial for evaluating salinity measurement accuracy in aquaculture environments.

In recent years, research on IoT-based Water Quality Monitoring (WQM) systems for aquaculture has grown significantly, particularly in salinity measurement. Accurate validation of salinity sensors is critical, given the dynamic and fluctuating nature of aquatic environments. For example, Jais et al. validated electrical conductivity (EC) sensor readings using a standard refractometer as a reference, demonstrating that calibration with conventional instruments like refractometers can substantially improve the accuracy of salinity data in IoT-based monitoring systems [9]. Similarly, Eso et al. employed manual refractometer readings as a calibration baseline for EC sensors used in shrimp pond monitoring systems [11].

However, refractometer-based validation presents several challenges. These include reliance on manual measurements by operators, which may introduce field data inconsistencies. Furthermore, water temperature significantly affects the refractive index, requiring temperature compensation or control for precise refractometer readings [12].

While IoT-based salinity sensors have gained popularity for real-time monitoring, refractometers remain widely used in aquaculture practices as a standard reference tool, particularly for validating and calibrating EC-based measurements [9], [11]. However, there is a fundamental difference in the measurement principles between EC sensors and refractometers: EC sensors detect the ionic concentration that influences the water's electrical conductivity, while refractometers estimate absolute salinity based on the total dissolved solids in the water. As a result, the outputs of these two methods are not always quantitatively aligned [6].

This paper studies and validates salinity data from an IoT-based Water Quality Monitoring (WQM) system by comparing it with refractometer measurements to assess accuracy and quantify error percentage.

2. METHOD

The research was conducted using an empirical approach from September to December 2023 at the ponds owned by the Public Service Agency for Aquaculture Production (BLUPPB) in Karawang. The scope of this study is to compare salinity measurements obtained from the Water Quality Monitoring (WQM) system with those from a refractometer used by the BLUPPB Karawang Laboratory. The comparison between WQM measurements and refractometer readings is primarily driven by field practice, where pond operators are accustomed to using refractometers for salinity measurement. By contrast, IoT-based WQMs are relatively new to them.

2.1. Tools and Materials

The tools used in this research include a Water Quality Monitoring (WQM) devices, refractometer, ESP32 microcontroller, Raspberry Pi Pico, solar panel, battery, board, mounting equipment, enclosure box, float, smartphone, bottles, and the monitoring application. The materials used in this study include pond water from BLUPPB Karawang, tissue, and distilled water (aqua-dest). The WQM devices are provided by a third party vendor, with limited information how the devices has been developed and calibrated. The vendor claimed the salinity sensors have been calibrated using the guideline provided by the salinity sensors manufacture. The WQM devices support multiparametric probe which include temperature, pH, dissolve oksigen, salinity, and ammonia. In this paper, we will focus on the performance of salinity sensors.

2.2. Variables and Research Stages

There are two variables in this study: the independent and dependent variables. The independent variable in this research is the pond water from each BLUPPB ponds. The dependent variable is the salinity value obtained from measurements, expressed in ppt (parts per trillion), using the WQM sensors and

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a refractometer. The research stages begin with a literature review and conclude with conclusions, as illustrated in Figure 1.

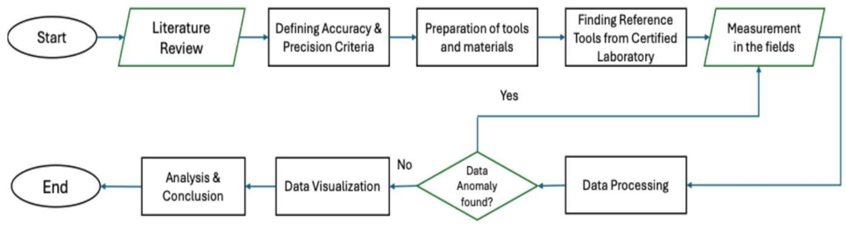

Figure 1. Flow-chart of Research Process

2.3. Research Procedures

Testing and validation of salinity values on the sensor were based on a combination of studies conducted by [5] and [13] with modifications. The testing and validation were carried out using 22 WQM (Water Quality Monitoring) devices installed in 22 tilapia ponds at BLUPPB Karawang, with 4 sampling points as shown in Figure 2. Each repetition was conducted every 5 minutes. This was done because the installed water quality monitoring sensors are set to collect data every 5 minutes. The measurements were conducted on 18, 20 and 21 October 2023 and indicated as the first, second, third trials respectively. The obtained salinity values were then processed using Microsoft Excel software to calculate the average salinity value, error percentage, accuracy percentage, repeated uncertainty (standard deviation), and precision.

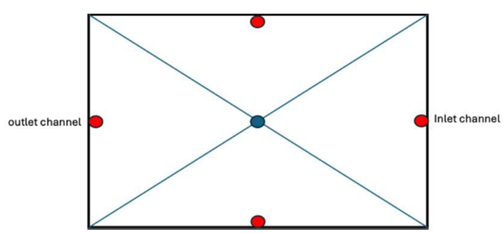

Figure 2. Data collection points. Red circles indicate data measurement points using a refractometer and blue circles using a WQM.

2.3.1. Mean Salinity

The mean salinity serves to represent the central tendency of salinity values obtained from multiple measurements. It is calculated using Equation 1 to provide a reliable estimate of the overall salinity level.

$$\bar{X} = \frac{1}{n}\sum_{n=1}^{n} X_n \tag{1}$$

X_n is the value of the n-th data point, and the total number of measurements is denoted by n

2.3.2. Salinity Measurement Accuracy

Measurement accuracy refers to the degree of closeness between the observed salinity values and those obtained from a reference measurement. Prior to determining accuracy, the error percentage is calculated using Equation 2.

$$\%\,\text{Error} = \left|\frac{Y_n - X_n}{Y_n}\right| \times 100\% \tag{2}$$

Where Y_n denotes the true value, and X_n denotes the value recorded by the measuring instrument.
Following the calculation of the error percentage, the accuracy percentage is subsequently obtained by subtracting the error value from 100%, as presented in Equation 3.

$$\%\,\text{Accuracy} = 100\% - \%\,\text{Error} \tag{3}$$

2.3.3. Precision of Salinity Measurement

Measurement precision refers to the degree of consistency or repeatability of salinity values obtained through repeated measurements. It is quantified using Equation 4, which assesses the proximity of each individual measurement to the overall mean value.

$$Precision = 1 - \left|\frac{X_n - \overline{X_s}}{\overline{X_s}}\right| \tag{4}$$

Where $\overline{X_s}$ is mean of all measurement data.

To ensure reliable estimation of precision, measurements were conducted with four repetitions. The corresponding repeated uncertainty is calculated as shown in Equation 5, which represents the standard deviation of the repeated measurements.

$$\Delta X = \frac{1}{n}\sqrt{\frac{n\Sigma X_i^2 - (\Sigma X_i)^2}{n-1}} \tag{5}$$

Furthermore, relative uncertainty (RU) is employed to evaluate the precision in relation to the mean value. A lower relative uncertainty indicates higher measurement precision. The formula for calculating relative uncertainty (*RU*) is provided in Equation 6.

$$RU = \frac{\Delta X}{X_s}\, x\, 100\% \tag{6}$$

3. RESULT & DISCUSSION

3.1. Salinity Measurement Data

Salinity measurements were carried out using two measurement tools, namely a Water Quality Monitoring (WQM) device and a refractometer. Each of the 22 WQM units, installed across 22 tilapia ponds at BLUPPB, was measured three times. The resulting salinity data collected from both instruments across all ponds are presented in Figures 3, 4, and 5.

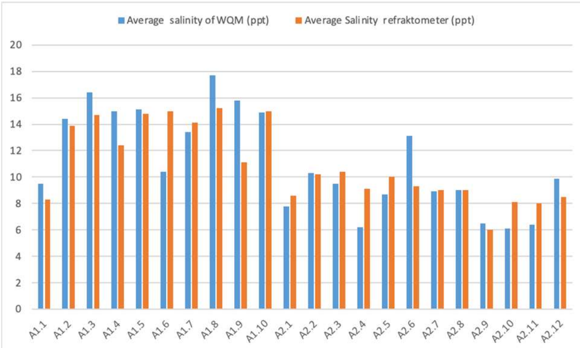

Figure 3. Salinity measurement results of WQM sensors and refractometer in the first trial

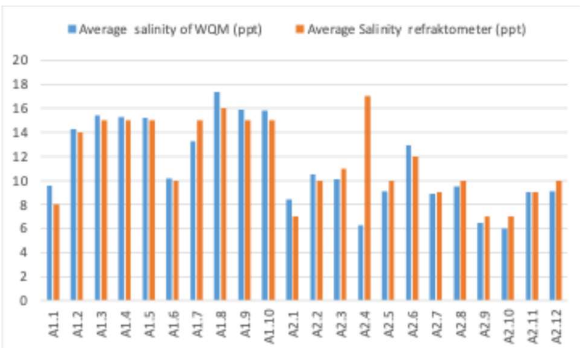

Figure 4. Salinity measurement results of WQM sensors and refractometer in the second trial

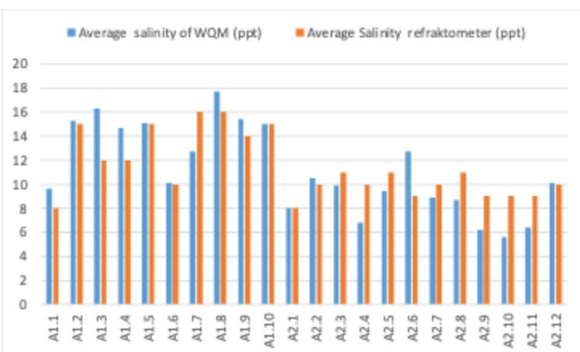

Figure 5. Salinity measurement results of WQM sensors and refractometer in the third trial

3.2. Accuracy of WQM Salinity Sensors

The accuracy of the WQM salinity sensor was evaluated by comparing salinity readings from 22 WQM devices against those obtained using a refractometer. Variations in error and accuracy were observed across different devices as well as across individual measurement repetitions. The average error rates recorded in the first, second, and third trials were 19.90%, 9.58%, and 16.21%, respectively. These levels of error directly influence the accuracy of the WQM measurements. Consequently, the average accuracy values for the respective trials were 80.10%, 90.42%, and 83.79%. Despite these results, the accuracy of the WQM salinity measurements are lower than the 95% accuracy compared to the previous studies reported in [5] [9].

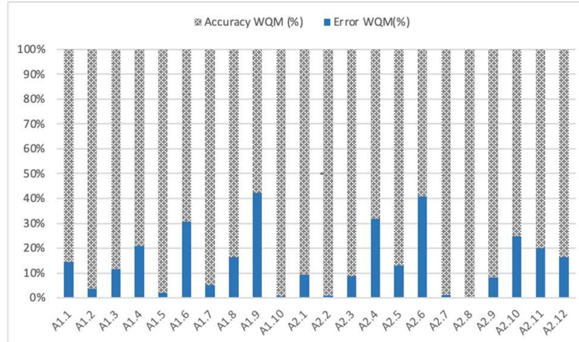

Figure 6. Percentage of errors of WQM salinity sensors in the first trial

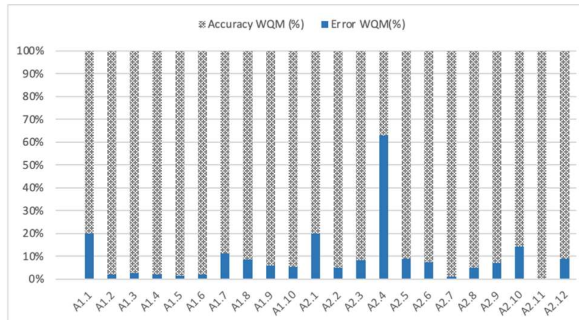

Figure 7. Percentage of errors of WQM salinity sensors in the second trial

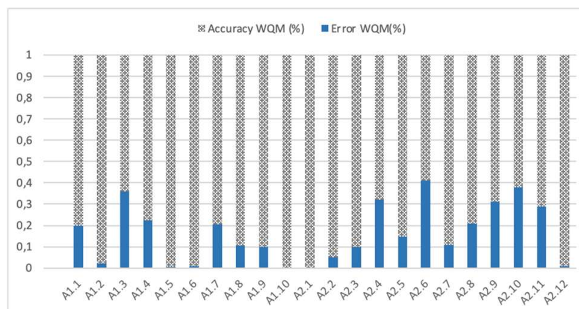

Figure 8. Percentage of errors of WQM salinity sensors in the third trial

The measurement errors observed in the WQM sensors do not yet comply with established standards. According to [14], [15], the maximum permissible error for sensor measurements should not exceed 5%. Sensor-related errors generally fall into three categories: constant, short, and noise errors. [16]. A constant error is evidenced by a long run of identical measurements that sit well above or below the regular sensor readings (Figure 9). A short error refers to an abrupt, high-magnitude change between two consecutive data points (Figure 10). Meanwhile, noise errors are identified by increased variance or fluctuation in sensor readings (Figure 11).

Sensor measurement errors can be attributed to several underlying factors, including hardware malfunctions, short-circuit connections, insufficient battery voltage, and calibration inaccuracies [17]. A constant error is often the result of sensor damage, typically linked to issues in the analog-to-digital converter (ADC). Short-circuiting may lead to either short or noise errors, characterized by abrupt fluctuations in sensor readings. When the battery is low, measurements may show both

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an constant mistake and random noise errors. Among these, calibration error is considered the most critical, as it can induce all three types of error—constant, short, and noise—simultaneously, as depicted in Figure 9. In the case of salinity sensors, calibration errors are commonly caused by variations in temperature and conductivity, given that the sensor's operating principle is based on water conductivity [7]. Detection of such errors can be achieved using four analytical methods: short and noise rules, linear least squares estimation (LLSE), autoregressive integrated moving average (ARIMA), and the hidden Markov model (HMM).

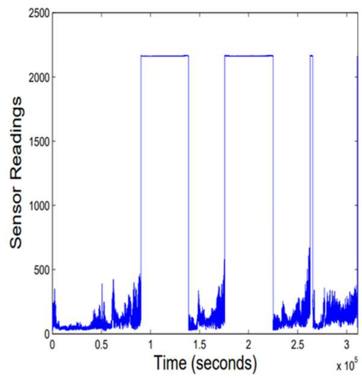

Figure 9. Constant error model of salinity sensors [16]

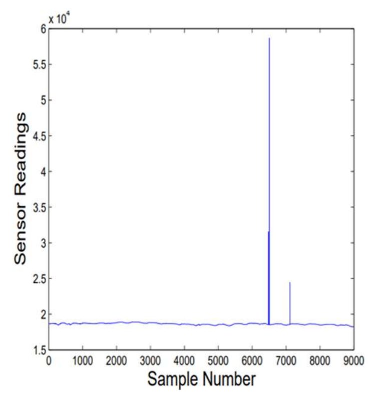

Figure 10. Short error model of salinity sensors [16]

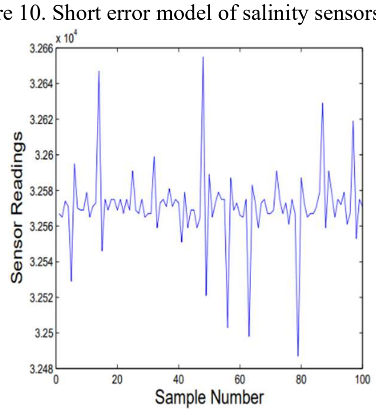

Figure 11. Noise error model of salinity sensors [16]

3.3. *Precision of WQM and Refractometer Salinity Sensors*

The precision of the WQM salinity sensor exhibited variability across different devices and measurement repetitions. The average precision values recorded during the first, second, and third trials were 0.7128, 0.7285, and 0.7174, respectively. These values indicate a higher degree of precision compared to the findings reported in [5], which documented a value of 0.9722. According to [18], the smaller the measurable resolution of a device, the greater its precision. Nevertheless, the precision level of the WQM still falls short of the salinity sensor standard, which requires a minimum precision of 0.01 [7]. One approach to improving measurement precision is to incorporate four electrodes, which enhances the sensor's resistivity.

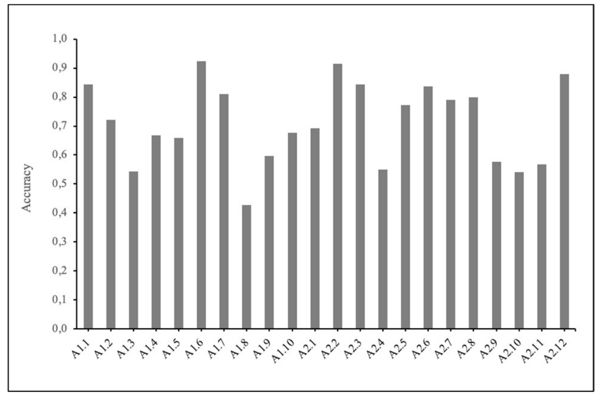

Figure 12. Accuracy of WQM salinity sensors in the first trial

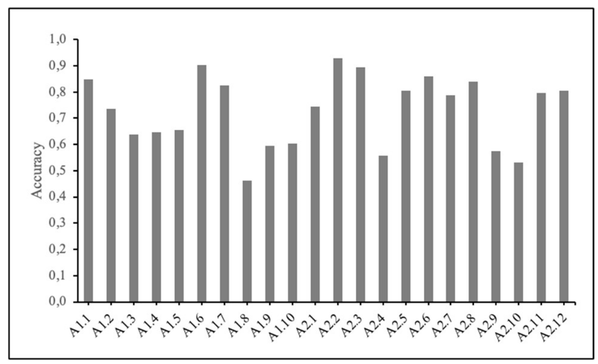

Figure 13. Accuracy of WQM salinity sensors in the second trial

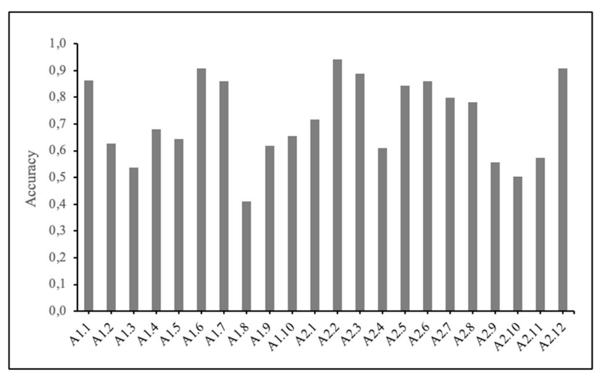

Figure 14.. Accuracy of WQM salinity sensors in the third trial

The consistency of the measurements cannot yet be deemed adequate. During the first trial, the WQM device recorded four data points at uniform time intervals, whereas the refractometer measurements were conducted at varying intervals. Furthermore, no repeated measurements were carried out during the second and third trials. Consequently, it was not possible to determine the standard deviation and the relative uncertainty of the WQM measurements.

3.4. *Comments on the use of Refractometer as Measurement Validator*

In field practice of saline tilapia aquaculture, daily salinity measurements are still predominantly made using refractometers. When we introduced a water-quality meter (WQM) at the BLUPPBP Karawang, pond staff tended to benchmark the WQM readings against a refractometer. This practice is also found in the recent tilapia study conducted in a seawater recirculating aquaculture system (RAS), where salinity monitoring was recorded using a refractometer [19]. This indicates that refractometers remain the practical instrument of choice among saline-tilapia farmers for in-situ measurements [19], [20], [21]. Meanwhile, IoT-based WQMs for aquaculture are indeed advancing; however, literature from the past five years still places them mainly at the prototype, integration or testing stage, with gradual adoption in trials of grow-out ponds (including tilapia), rather than as "everyday tools" for the majority of farmers [22], [23], [24].

In several prototypes and field deployments, EC-based salinity sensors are calibrated against a refractometer so that their EC-derived readings approximate the refractometer-reported 'salinity,' with the refractometer serving as the practical field reference [9], [23], [25]. Validating WQM readings against a refractometer presents a paradox. On one hand, farmers are familiar with—and tend to trust—refractometers. On the other hand, experts argue that the two instruments rely on fundamentally different measurement principles and measurands. EC-based methods essentially estimate Practical Salinity (PSS-78) from the electrical conductivity of ionic substances in seawater or brackish water [6]. By contrast, a refractometer infers *absolute salinity* from the refractive index, which is sensitive to total dissolved content, including both ionic and non-ionic solutes. Consequently, non-standard waters (i.e. seawater with urea) can exhibit discrepancies due to the presence of non-ionic constituents [12]. This pattern is consistent with reviews of salinity-measurement technologies and studies on the effects of dissolved organic matter (DOM) on optical versus conductivity readings [6], [12]. For reasons of availability, cost, and ease of use, refractometers are therefore often employed as the field comparator/validator for IoT WQM salinity readings in tilapia aquaculture, although these differences in principle must be accounted for when interpreting results [9], [12].

Although this paradox is indeed observed in the field (tilapia ponds at BLUPPB) and in other empirical studies, refractometers are often used as a reference/calibrator for conductivity-based salinity sensors. For example, in a milkfish monitoring system test, the researchers explicitly compared an Atlas Scientific salinity sensor with a refractometer. They presented a sensor-versus-refractometer table for seawater and mixed samples, showing a residual error of approximately 4%. This indicates that calibration must account for the local water matrix [26]. Conversely, during field validation of an aquaculture IoT system, the researchers used an Atago 2483 Salinity Refractometer as the reference instrument and reported a mean absolute percentage error (MAPE) of approximately 1.85% for the EC sensor, underscoring the role of an optical reference in reducing bias and assessing reliability [25].

The impact on accuracy is evident: in an IoT implementation for Litopenaeus vannamei aquaculture ponds, following calibration/validation, salinity accuracy was reported at 99.49% (or an error rate of 0.41%), indicating that the system is suitable for real-time monitoring [23]. This accuracy-enhancement approach aligns with the practice of validating low-cost sensors against professional instruments and augmenting measurements with modeling (e.g., linear regression) to correct readings—as recommended in a 2024 Heliyon study [9]

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However, a fundamental limitation persists refractometers measure total refractive index (affected by both ionic and non-ionic solutes), whereas electrical conductivity (EC) sensors infer Practical Salinity (PSS-78) from ionic conductivity. Consequently, calibration against a refractometer can become localized or matrix-specific (as reflected by residual errors in tests using seawater and mixed samples), and results may drift when the non-ionic composition/dissolved organic matter (DOM) changes or when manual readings lack consistency—underscoring the need for iterative calibration procedures and transparent reporting of measurement uncertainty [26].

3.5. *Challanges to use IoT-based WQM for Real Time Measurement*

The use of Internet of Things (IoT)–based water quality monitoring (WQM) for real-time assessment indeed promises rapid access to measurement results that can expedite monitoring, inform decision-making, and enable timely water-treatment interventions. However, several challenges must be carefully considered.

First, it is essential to calibrate the WQM device using reference-grade instrumentation and to test it in an accredited laboratory, so that the device is evaluated under fully controlled conditions. Measurements at the BLUPPB ponds showed marked differences between readings from the IoT-based WQM and a refractometer. The refractometer was used solely as a practical point of comparison and cannot be considered a reference instrument. Beyond the difference in measurement principles, we also lack information on the instrument's history, including whether it has been calibrated as a reference device. Nevertheless, from a measurement-practice standpoint, these discrepancies provide helpful feedback for the WQM vendor to perform calibration with reference-grade tools in an accredited testing laboratory.

Second, IoT-based WQM offers real-time measurements. The primary challenge of real-time monitoring is that instruments must be left in place on site for extended periods. Because a salinity sensor measures ionic content in water, its sensitivity must be continuously maintained; over time, the sensor's protective tube requires routine cleaning. Parra et al. [27]. Likewise, we recommend cleaning multiparameter probes to protect sensors from environmental distortions caused by dissolved substances, epiphytes, and other organisms. Based on our experience, the sensor should be cleaned every 10 days, or at the latest, every two weeks, as increasing coverage by silt, algae, or aquatic organisms progressively degrades measurement accuracy. Routine maintenance poses a practical challenge for pond personnel, who therefore tend to prefer portable IoT WQM devices or portable refractometers. An adequately designed outer

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casing and exclusion barriers for invertebrates and ichthyofauna, together with correct installation, are required to prevent clogging of the water-sampling tube by sediment or fauna [27].

Third, the accuracy and reliability of salinity testing using IoT-based water quality monitors (WQMs) are strongly influenced by sensor quality, calibration procedures, and temperature compensation consistent with PSS-78 [28]. In brackish waters that are prone to biofouling and corrosion, low-cost sensors tend to experience drift and performance degradation; therefore, materials that are corrosion/biofouling-resistant, capable of maintaining long-term stability, and offer higher sensitivity are required so that maintenance intervals can be extended [29], [30], [31]. To achieve optimal results and prevent malfunctions, the use of sensors equipped with self-cleaning mechanisms is recommended [32]. As argued by Nalakurthi et al., there is a need to investigate and develop commercially viable, low-cost sensors with anti-fouling properties for water-quality assessment [32]. Unfortunately, such functions require robust power, and inexpensive sensors cannot adequately support self-cleaning mechanisms.

4. CONCLUSION

The average error values recorded in the first, second, and third measurement trials were 19.90%, 9.58%, and 16.21%, respectively. These values exceed the acceptable error threshold for salinity sensors, which is set at 5%. The elevated error levels may be attributed to various factors, including sensor damage, short-circuit connections, insufficient battery power, and calibration inaccuracies. The average precision of the WQM device across the three trials was 0.7128, 0.7285, and 0.7174, respectively falling short of the standard precision requirement of 0.01 for salinity sensors. One potential method for improving sensor precision is the integration of four electrodes to enhance the sensor's resistivity characteristics.

Calibration and resilience testing in controlled environments using reference measurement tools are essential for ensuring and improving device accuracy. Furthermore, IoT-based salinity measurements for real-time *in situ* monitoring necessitate routine sensor maintenance and periodic calibration. Future research and commercialization efforts should focus on developing sensors that are both affordable and highly accurate, with enhanced resistance to corrosion and biofouling, to strengthen user confidence in IoT-based water quality monitoring (WQM) systems. Additionally, the integration of self-cleaning capabilities warrants thorough investigation, as it can significantly reduce maintenance requirements and promote wider adoption of IoT-based WQMs compared to traditional handheld refractometers.

The use of refractometers as comparative measurement tools remains widely accepted among aquaculture practitioners, as they are not only practical but also familiar instruments trusted by fish farmers. However, to validate the accuracy and precision of IoT-based salinity measurement devices, it is essential to provide adequate education and establish a common understanding that these devices are designed to measure practical salinity, rather than absolute salinity. Therefore, their performance should be compared against reference instruments that are also capable of measuring practical salinity.

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NOMENCLATURE

Notations Equation (1):

$\overline{X}$ = mean salinity

n = total number of data points

X_n= value of the n-th data point

Notations Equation (2) and (3):

% Error = percentage of error

Y_n = Actual Value

X_n = value measured by the instrument

Notations Equation (4):

X_n = value of the *n*-th measurement

$\overline{X_s}$ = mean of all measurements

Notations Equation (5):

ΔX = repeated uncertainty (standard deviation)

X_i = i-th data point in repeated measurements

n = number of repetitions

Notations Equation (6):

RU = relative uncertainty

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