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An Open-Source Solution for Water Conductivity Monitoring Using Arduino and Low-Cost Components

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Abssstract: Water conductivity is a key parameter in water quality assessment, reflecting dissolved ion concentrations and serving as an indicator of both pollution sources and natural variability. Continuous, high-frequency monitoring of conductivity is particularly valuable for capturing short-term fluctuations caused by rainfall, contaminant discharges, or biological processes, patterns often missed by discrete sampling. However, the high cost of commercial conductivity meters limits their use in low-resource settings, educational projects, and citizen science initiatives. This study presents the development and evaluation of a low-cost, three-electrode conductivity sensor based on the Arduino platform and inexpensive, widely available materials such as stainless-steel electrodes. A segmented calibration strategy was employed to address the nonlinear voltage-conductivity relationship, combining linear regression for low-conductivity values and a power-law fit for higher ranges (0–50 mS/cm). Additionally, the effect of electrode surface treatment was assessed, showing substantial improvement in measurement accuracy, with mean relative error reduced from 56% to 18%. Although the sensor's absolute accuracy remains lower than that of commercial or some other low-cost designs, its performance is suitable for detecting abrupt conductivity changes associated with contamination events in freshwater systems. This makes it a viable tool for environmental monitoring where low cost and broad spatial coverage are priorities.

Palavras-Chave – Electrical conductivity; Sensor development; Continuous monitoring

INTRODUÇÃO

Water is essential for human health, agriculture, sanitation, and climate regulation. Ensuring water quality is critical to prevent disease and protect public health. Investments in water treatment and monitoring have been shown to significantly reduce waterborne illnesses (Khodaparast et al., 2024). For every dollar invested in water quality monitoring, up to $5.20 can be saved on healthcare and productivity costs (Srivastava et al., 2025). Regular monitoring is therefore a cost-effective strategy for managing water resources, safeguarding human well-being, and understanding ecosystem dynamics.

Among the parameters commonly used in water quality assessments, electrical conductivity (EC) is particularly valuable due to its direct relationship with the concentration of dissolved ions.

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Studies have shown that elevated conductivity typically reflects the presence of ions such as nitrates, chlorides, and phosphates (Pule et al., 2015). Many aquatic organisms are sensitive to changes in ionic concentrations (Parra et al., 2015), affecting the biogeochemical cycles of rivers, lakes, and reservoirs. Sudden increases in conductivity levels may also indicate contamination from agricultural runoff, industrial discharges, or untreated sewage (Harwell et al., 2008). EC reflects salinity, pollution levels, and general water chemistry, offering rapid insight into both natural variability and anthropogenic impacts (APHA, 2017; Bartram and Ballance, 1996).

The need for accessible water quality sensors is increasing globally, especially in regions facing rapid urbanization, agricultural runoff, or poor water infrastructure. Traditional centralized monitoring networks often fail to capture spatial and temporal variability in water quality (UNESCO, 2021). Commercial conductivity meters provide high accuracy but often rely on expensive equipment for large-scale monitoring systems, mainly in resource-limited settings, community-based monitoring programs, and educational initiatives. Commercially available conductivity meters typically cost more than $1000 (Chapin et al., 2014). This economic barrier for large-scale monitoring has driven growing interest in open-source and do-it-yourself (DIY) technologies, which provide cost-effective and customizable alternatives without compromising performance (Maag et al., 2018; Zúñiga et al., 2022). The emergence of platforms such as Arduino and Raspberry Pi has facilitated the development of a wide range of low-cost environmental sensors, including systems for monitoring pH (Zhang et al., 2021), turbidity (Ravindra et al., 2020), temperature, dissolved oxygen (Mutia et al., 2020), and electrical conductivity (Chapin et al., 2014; Serrano-Finetti et al., 2019; Carminati and Luzzatto-Fegiz, 2017; Banna et al., 2014; Benjankar and Kafle, 2021; Parra et al. 2023).

Numerous studies have proposed low-cost conductivity meter probes, either by developing custom devices using passive electrical components (Serrano-Finetti et al., 2019; Carminati and Luzzatto-Fegiz, 2017) or by evaluating open-source, commercially available low-cost conductivity meters (Blanco-Gómez et al., 2023; Fulton et al., 2023; Lockridge et al., 2016). Although these open-source commercial sensors (e.g., 426-DFR0300-H) demonstrate good accuracy and are approximately 85% less expensive than standard commercial sensors (Fulton et al., 2023), sensors built solely with passive electrical components can be up to 99% cheaper than reference-grade sensors, typically costing less than 10 dollars.

Serrano-Finetti et al. (2019) developed a conductivity meter using two acorn nuts as electrodes, achieving a measurement range from 0.35 to 6.18 mS cm^{-1}. The device was tested over a period of nearly 100 days, yielding a mean relative error of 2.3% of the full scale. Under laboratory conditions, the accuracy improved to an error of 0.03 mS·cm^{-1}. Similarly, Carminati and Luzzatto-Fegiz (2017) constructed a probe using gold-plated pins from micro-USB connectors as electrodes, operating across a broader range of 10 to 1500 mS·cm^{-1}. Their device achieved errors of approximately 1% over the full scale and had a cost of around 10 dollars.

Banna et al. (2014) developed a conductivity meter capable of measuring conductivity in the range of 0 to 20 mS·cm^{-1}. However, the accuracy of the probe was not quantified due to the lack of reference conductivity values for the test solutions. Nonetheless, the study demonstrated that the probe's readings were not affected by the water flow rate and remained consistent over one-month period of measurements, with observed variations likely within the device's measurement uncertainty. Additionally, Benjankar and Kafle (2021) proposed a low-cost turbidity sensor, which exhibited an average error of approximately 6% in laboratory tests and 11% in a six-month field deployment.

While most low-cost conductivity meters operate based on the conductive measurement principle, some devices have been developed using the inductive principle, where a powered copper coil generates an electromagnetic field, inducing a current in a secondary coil. Using the inductive approach, Parra et al. (2015) built a probe capable of measuring conductivities ranging from 0.6 to 74 mS·cm^{-1}, with a mean relative error of 2%, comparable to the accuracy of conductive-type low-cost meters.

Although many low-cost conductivity meters have been developed based on two- or four-electrode configurations, few studies have evaluated three-electrode designs. In addition, little attention has been given to optimizing measurement accuracy by addressing electrode polarization effects and mitigating electrochemical reactions that can significantly affect sensor readings.

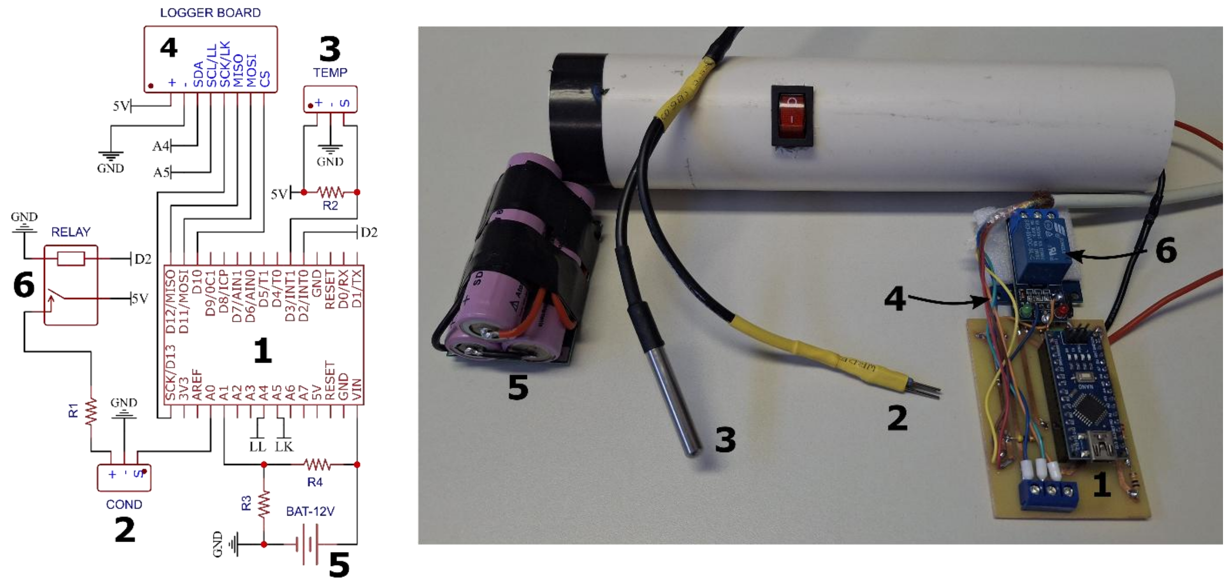
Considering the importance of measuring conductivity and the lack of studies focusing on improving of low-cost conductivity meters available on the market, this study aims to present the development of an affordable three-electrode conductivity sensor based on the Arduino microcontroller platform. In addition, the effect of electrode surface treatment on minimizing electrochemical reactions in low-cost conductivity measurements is evaluated. Designed for ease of replication and broad accessibility, the sensor employs stainless steel electrodes and a basic voltage divider circuit. Calibration was performed using deionized water with incremental additions of table salt (NaCl), allowing for the accurate estimation of ionic concentration across a practical range.

MATERIALS AND METHODS

Sensor Design and Hardware Components

The low-cost conductivity sensor was built using an Arduino Nano developed board (Figure 1; component 1), which features the ATmega328P microcontroller. This microcontroller includes a 10-bit analog-to-digital converter (ADC), enabling voltage measurements with a resolution of 1024 discrete levels. The board was selected for its compact size, affordability, and compatibility with a wide range of peripheral devices.

Figure 1. Schematic diagram of the conductivity measurement circuit alongside a photo of the assembled system. The main components include: (1) Arduino Nano microcontroller; (2) conductivity probe with stainless steel electrodes; (3) water temperature sensor; (4) datalogger consisting of a real-time clock (RTC) to maintain date and time settings during power loss and a microSD card module for data storage; (5) battery for portable power supply; and (6) relay used to disconnect the probe between measurements, minimizing electrolysis and conserving energy.



Electrical conductivity measurement relies on the ability of dissolved ions to carry electrical current between electrodes in solution. While deionized water exhibits negligible conductivity due to the absence of free ions, the addition of salt (e.g., NaCl) induces dissociated ions (Na^+, Cl^-), substantially increasing the solution's conductivity. Sensor geometry also plays a key role in measurement accuracy. Specifically, the distance between electrodes and their surface area, quantified by the cell constant (K), must be accounted for and calibrated against a reference sensor (Mitchison et al., 2020). The measurement system is based on a voltage divider circuit, in which the electrical resistance of the water sample constitutes one leg of the divider. By applying a known 5V input voltage and measuring the resulting voltage drop across the sample using the Arduino's 10-bit ADC on the A0 pin (Figure 1), the system directly estimates the sample's electrical conductivity.

The sensor probe (Figure 1; component 2) consists of three stainless steel electrodes (AISI 316L, 1.2 mm diameter), selected for their excellent corrosion resistance, mechanical robustness, and widespread availability. These electrodes are arranged in a fixed configuration with 5 mm spacing. To account for the temperature dependence of electrical conductivity, a digital temperature sensor (DS18B20) was integrated into the system (Figure 1; component 3). This sensor offers an accuracy of ±0.5 °C over the range of −10 °C to 85 °C, enabling temperature compensation of conductivity measurements.

Although calibration data in the laboratory were acquired in real time via the Arduino IDE's serial monitor, a data logging module (ID:8122 Deek-Robot) was integrated into the system to enable continuous field monitoring (Figure 1; component 4). This minilogger board incorporates a DS1307 real-time clock and a microSD card reader, allowing time-stamped data storage. To ensure autonomous operation in remote areas, a 12 V rechargeable power supply was implemented, consisting of three 8800 mAh 4.2 V LiPo batteries connected in series and managed by a 3S 40A 12 V PCB battery management system with cell balancing capability (Figure 1; component 5).

To reduce power consumption and minimize electrochemical degradation (e.g., electrode polarization or electrolysis), a relay was integrated into the circuit to disconnect the electrodes between measurement intervals (Figure 1; component 6). This strategy prevents continuous current flow through the sample, preserving both electrode and sample integrity, thereby improving measurement consistency over time. For field deployment, all electronic components were housed within a 50 mm diameter PVC pipe, 30 cm in length, sealed at both ends with 5 mm thick end caps. A switch was installed between the battery and microcontroller circuits to facilitate powering the system during field operations. All components used were low-cost and non-toxic, suitable for use in classroom and field conditions. The total cost of materials was under 10 dollars, including the Arduino board, stainless steel electrodes, breadboard, resistors, and wiring.

Calibration and Experimental Setup

The calibration procedure was divided into two experimental setups; both were conducted in the laboratory under controlled conditions. The first setup aimed to evaluate the robustness and performance of the conductivity probe using two different electrode treatments. In the first experiment, three stainless steel electrodes were tested in their untreated state, without any surface modification. In the second experiment, the same configuration was used, but the electrodes were thermally treated and coated with a thin layer of silicone resin, constituting the treated state. This treatment was applied to enhance signal consistency, since electrochemical reactions at the electrode surface can generate background noise and affect the accuracy of conductivity measurements.

In both setups, the electrodes were immersed in a small container filled with test solutions of varying electrical conductivities. Four test solutions were prepared with target conductivities of approximately 100, 7,000, 23,000, and 47,000 µS/cm. Each solution was obtained by dissolving precise masses of sodium chloride (NaCl) in deionized water. For each conductivity level, the solution was thoroughly mixed, and voltage readings from the developed conductivity sensor were recorded at 1-second intervals for approximately 3 minutes to ensure stabilization and reliable measurement. Once signal stabilization was achieved, electrical conductivity was measured using a commercial conductivity meter (CastAway-CTD), which served as the reference standard. This device has a resolution of 1µS/cm and an accuracy of ±0.25% (±5 µS/cm). The temperature of each solution was also monitored and maintained at room temperature (21 °C ± 1°C) to avoid temperature-induced variations in conductivity readings (APHA, 2017).

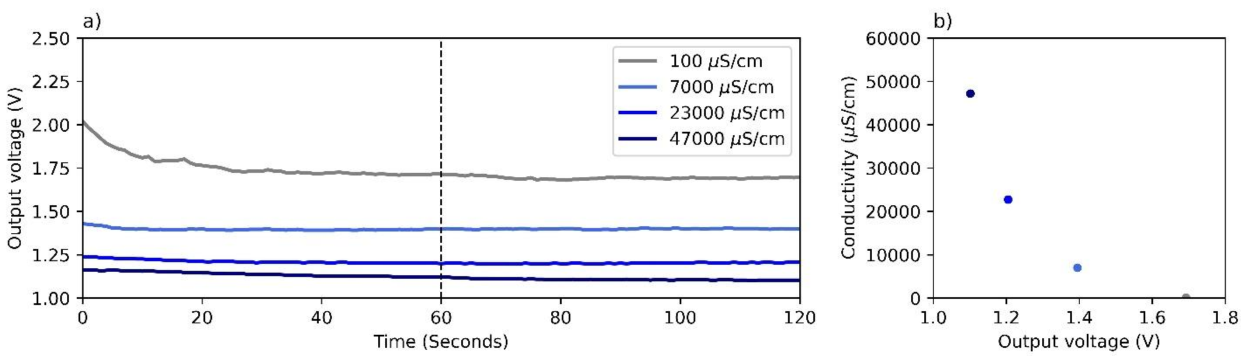
Each experimental condition was repeated three times for both electrode treatments. The first two replicates were used to generate calibration data, with average voltage values computed and used for calibration curve fitting. The third replicate was used for probe validation. Calibration curves were developed by fitting linear, power, and exponential regression models to the data, and the best-fitting equation was selected based on the highest coefficient of determination (R^2). Sensor performance during the validation stage was assessed using the root mean square error (RMSE) and relative error.

A final analysis was conducted using a similar experimental setup, applying the previously derived calibration curve. In this case, a larger tank was used, and the conductivity was gradually increased from 14 to 26,000 µS/cm in increments of approximately 2,500 µS/cm. This experiment was performed exclusively with the treated electrodes to further assess sensor performance under refined data analysis.

RESULTS

The voltage output signal of the developed conductivity probe was evaluated across a conductivity range from 14 µS/cm to 50,000 µS/cm, using a CastAway-CTD sensor as reference. In all trials, the output voltage consistently decreased with increasing conductivity, a behavior that aligns with the voltage divider principle. As water conductivity increases, its electrical resistance decreases, enabling more current to flow through the series resistor. This leads to a higher voltage drop across the resistor and, consequently, a lower voltage measured at the analog input pin of the microcontroller (Figure 2).

Figure 2. Output voltage response from experiments performed with treated electrodes. a) Time series of output voltage during the first 120 seconds of measurement across different conductivity solutions. The dashed line indicates the stabilization period, defined as the interval during which output voltage variability falls below 1%. b) Relationship between the stabilized output voltage signal (output voltage averaged between 60 and 180 seconds of measurements) and electrical conductivity, as measured by the reference conductivity meter.



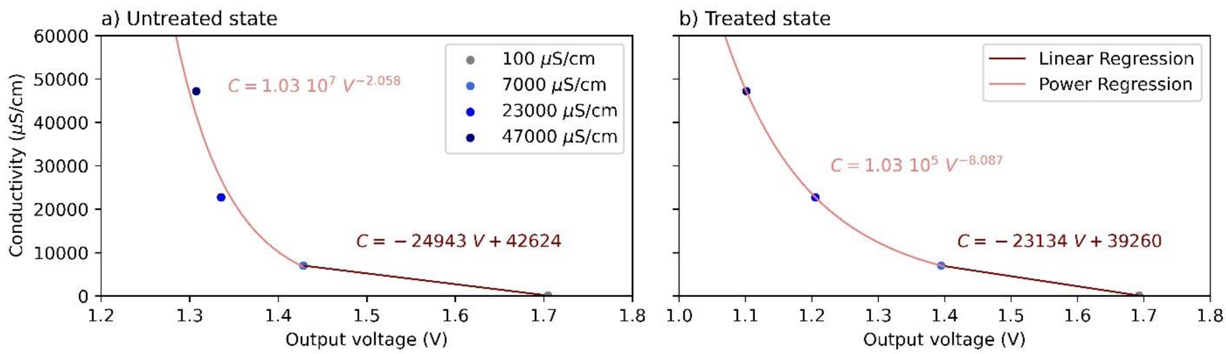
Signal stabilization

The probe exhibited rapid signal stabilization, particularly at higher conductivity levels (Figure 2a). Stabilization was defined as the point at which voltage variability dropped below 1%. Across all tested solutions, this threshold was reached within approximately 60 seconds. For higher conductivities (>7,000 µS cm^{-1}), the signal stabilized almost immediately, often within the first 5 seconds of measurement. This fast response indicates the sensor's suitability for real-time or in-situ monitoring where short measurement times are essential.

Calibration curves

Calibration between output voltage and conductivity was evaluated using linear, exponential, and power-law regression models (Figure 3). Given the evident nonlinearity of the relationship, a segmented calibration approach was adopted. For low conductivities (<7,000 µS cm^{-1}), a linear regression provided an adequate fit, while for higher conductivities, a power-law model offered improved accuracy. The segmentation threshold was slightly different for untreated (V_{lim}=1.42 V) and treated electrodes (V_{lim}=1.40 V).

Figure 3. Relationship between output voltage signal and electrical conductivity, as measured by the reference conductivity meter, for a) untreated and b) treated electrodes. Dark red lines represent linear calibration curves, while light red lines indicate power-law calibration fits, each applied to different voltage ranges.



The treated electrodes outperformed untreated ones in terms of calibration accuracy. For high-conductivity ranges, the power-law model yielded an R^2 of 0.999 for the treated electrodes, compared to 0.975 for untreated ones. This improvement suggests that surface treatment enhances the electrochemical stability of the electrodes and reduces signal noise due to interface effects between the electrode surface and the electrolyte.

Sensor validation

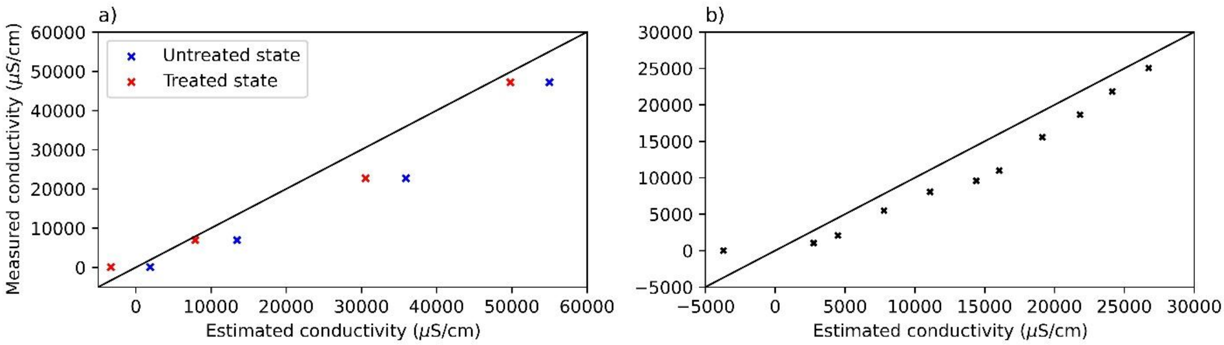
Validation was performed by comparing the estimated conductivity values with those measured by the reference sensor (Figure 4a). For untreated electrodes, the root mean square error (RMSE) was 836 µS/cm, with a mean relative error of 56%. The treated electrodes significantly improved the performance, reducing the RMSE to 448 µS cm^{-1} and the mean relative error to 18%.

A second validation test was carried out using the treated electrodes with finer conductivity increments (~250 µS/cm), resulting in a similar RMSE of 325 µS cm^{-1} (Figure 4b). However, the mean relative error increased to 39%, likely due to the higher sensitivity of the calibration function to small fluctuations in voltage when the conductivity steps are narrow. Despite this increase, the sensor still demonstrated acceptable accuracy for semi-quantitative environmental applications.

DISCUSSION

This study describes the development and validation of a low-cost conductivity sensor capable of measuring a wide range of conductivities, from approximately 0 to 50 mS/cm. Most low-cost conductivity meters reported in the literature target different conductivity ranges, varying between narrow and broad scales. For example, some studies have developed sensors designed primarily to distinguish between distilled and freshwater, typically covering ranges from 0 to 2 mS/cm (Visco et al., 2023; Fulton et al., 2023). In contrast, other studies present sensors intended for detecting transitions between freshwater and seawater, with operational ranges from approximately 10 to 1,500 mS/cm (Carminati and Luzzatto-Fegiz, 2017). Based on our analysis and comparisons with previous studies, the measurement range of each probe appears to be driven more by the intended application than by inherent technical limitations of the sensor designs. The developed sensor demonstrated the ability to differentiate between deionized water, freshwater, and seawater. Additionally, it exhibited rapid signal stabilization, particularly at conductivity values above 7 mS/cm. For lower conductivity values, which are typical of freshwater environments such as lakes and rivers, stabilization was achieved within 1 minute. Notably, few previous studies explicitly discuss sensor stabilization times, making direct performance comparisons challenging.

Figure 4. Sensor validation. Distinct markers represent data from different validation trials, comparing predicted and measured conductivity values. The 1:1 line indicates perfect agreement. a) Validation results for both untreated and treated electrodes (4 validation points each). b) Refined validation for the probe with treated electrodes, using additional data points.



To address the nonlinear relationship between voltage and conductivity, a segmented calibration approach was adopted. Linear regression was applied in the low-conductivity range, while a power-law fit was used for higher conductivity values. This strategy enabled the sensor to achieve reasonable accuracy across the full measurement range, making it suitable for specific applications, particularly for detecting anomalies in freshwater systems such as rivers and lakes. Potential applications include monitoring contamination from agricultural runoff, industrial discharges, and untreated sewage (Harwell et al., 2008).

The surface treatment of the electrodes played a crucial role in enhancing sensor performance. Treated electrodes showed a stronger correlation with reference measurements ($R^2 = 0.999$) and a significant reduction in both roots mean square error (RMSE), from 0.84 to 0.45 µS/cm, and mean relative error, from 56% to 18%. Despite these substantial improvements, the three-pin electrode design still exhibited relatively poor performance compared to other low-cost conductivity meters reported in the literature, which typically report mean relative errors below 6% for their target applications (Parra et al., 2015; Benjankar and Kafle, 2021; Carminati and Luzzatto-Fegiz, 2017).

Overall, the developed sensor offers a practical and low-cost solution for environmental monitoring, particularly for detecting abrupt changes in conductivity commonly associated with water contamination events. It represents a viable alternative to commercial conductivity meters for many applications where high absolute accuracy is not critical, but where spatial mapping or relative variation is of primary interest. Future work should focus on optimizing electrode surface treatments to enhance the performance of this and other low-cost conductivity sensors. Additionally, exploring adaptive calibration techniques could further improve measurement accuracy across the full operational range.

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