Design and Analysis of Electrical Conductivity Sensor for Water Quality Management in Sustainable Agriculture

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ABSTRACT

Water quality management is essential for sustainable agriculture, environmental protection, and public health. Among various water quality parameters, electrical conductivity (EC) is a key indicator of dissolved ions and nutrient concentration, making it indispensable for irrigation management, fertigation, hydroponics, and water resource monitoring. This study presents the design and development of a low-cost Internet of Things (IoT)-enabled EC sensor for modern fertigation systems. Unlike many existing low-cost EC sensors that often suffer from poor accuracy and inconsistent performance, the proposed system is designed to provide accurate, reliable, and real-time water quality monitoring. The developed system integrates a total dissolved solids (TDS) and EC sensor probe, a DS18B20 temperature sensor for temperature compensation, an ESP32 microcontroller, electronic circuits and an IoT cloud platform for remote monitoring and data visualization. The sensor was experimentally validated using standard conductivity solutions and benchmarked against a commercial-grade Hanna Instruments EC meter. Experimental results demonstrate excellent agreement with the existing TDS product and reference instrument, producing accurate EC measurements and a strong correlation between TDS and EC values. The proposed IoT-enabled EC sensor provides a practical and cost-effective solution for continuous water quality monitoring in precision agriculture and environmental applications. Furthermore, this work supports the United Nations Sustainable Development Goals (SDGs) by contributing to SDG 6 (Clean Water and Sanitation) through improved water quality monitoring, SDG 9 (Industry, Innovation and Infrastructure) through the use of IoT platform, and SDG 12 (Responsible Consumption and Production) by providing potential efficient water and nutrient management for more sustainable agricultural practices.

Keywords: Electrical Conductivity, Internet of Things, Fertigation, Sensor Calibration, Precision Agriculture, Water Monitoring

INTRODUCTION

Water is one of the most important natural resources that every ecosystem hosts. All living organisms need water to grow and survive. Nowadays, this problem is a worldwide issue affecting many countries by almost all counts [1]. Water quality should be monitored so authorities can take immediate precautions in the event of contamination. Protecting the environment, besides public health, relies on any measure taken to monitor water quality. Traditional approaches to assessing quality are usually expensive and long-term. It would be necessary to measure water quality parameters accurately for several specific uses, such as industrial activities, agricultural management, and environmental monitoring.

Electrical conductivity (EC) is one of the most crucial measurements in assessing water quality (WQ) [2,3] when measuring dissolved ions such as salts and minerals. What is essential for environmental health and

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safety, therefore, is that high EC values may signify contaminants; low levels may indicate pure water. Quite numerous in agriculture, EC sensors are applied to measure salt and nutrient levels in irrigation water, especially those automated intelligent fertigation systems. This is the only way to achieve optimum plant and produce growth since these sensors avoid too much salt that would harm the plant and decrease its yield.

Innovative fertigation systems depend on real-time data for intelligent nutrient supply and water use decisions. It is at this point that the precision of EC sensors becomes paramount. In such cases, the accuracy and reliability of the low-cost EC sensors on Internet of Things (IoT)-based fertigation systems would sometimes be said to require improvement since their results may differ significantly from the high caliber conductivity meters, which are used in laboratories. Hence, due to this difference, a big challenge is posed to farmers and agricultural managers, who rely on accurate measures to maintain the meticulous balance of nutrients in irrigation water. Excessive and insufficient fertilization pollutes plant health and results in crop losses and financial losses when inaccurate EC values lead to it.

This situation has necessitated the design of more accurate and reliable substitutes, which can easily be incorporated into intelligent fertigation systems because of the drawbacks in the currently available low-cost EC sensors. It aims to develop an EC sensor designed to be highly accurate, as current models produced by Hanna Instruments, and at the same time, easy to use and widely applicable with a reasonable cost [1]. Hence, this research intends to augment the efficiency of water quality monitoring for agricultural applications, emphasizing cost, practicality, and accuracy that will eventually aid in crop management and sustainability.

The intelligent fertigation systems will work properly if the water quality is managed correctly. These systems employ advanced technologies to optimize resources and improve crop yield. Unfortunately, the low-cost EC sensors available on the market still do not have good enough accuracy and reliability. Low-cost sensors usually produce results that are way out of laboratory-grade meters, thus posing problems for farmers and agronomists who base their nutrient management on precise measurements. The deviation from accuracy can cause over-fertilization [2] or under-fertilization, which may lead to loss of crops, reduced yield, and economic loss. Moreover, the existing EC sensors for IoT-based fertigation systems cannot meet the precision demanded by the best agricultural practices to necessitate improvement.

Numerous types of research on the EC sensor for water quality monitoring measurement in the fertigation system have been studied, and the findings of the studies are tabulated and discussed. Table 1 shows the significant results of the electrical conductivity sensor for water quality measurement in the fertigation system.

Table 1. Related research work

Paper	Method	Results	Limitation
4	Developed a water quality monitoring system using real-time multi-sensor arrays (pH, turbidity, and TDS sensors) and adaptive filtration systems. Data was processed through wireless data transmission through microcontrollers.	Enabled precise, real-time monitoring and adaptable filtration for various water sources, supporting safe drinking water and environmental protection.	High initial costs for system deployment; frequent calibration and maintenance are required to ensure accuracy.
5	Reviewed advancements in transducer technology for water quality monitoring, including optical, electrochemical, and MEMS-based sensors. Focused on multi-parameter sensors for monitoring pH, conductivity, and dissolved oxygen.	Improved sensor reliability and adaptability in harsh environments, aiding effective environmental monitoring and multi-parameter measurements.	Challenges with sensor fouling, calibration drift, and the need for periodic recalibration to maintain accuracy in long-term deployments.
6	Designed an Arduino-based, low-cost, open-source conductivity meter using a	Provided an affordable and accessible solution for	Limited scalability and accuracy compared to

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	handmade conductivity cell. Conductivity was measured through programmed Arduino hardware.	environmental monitoring in resource-limited settings, enabling grassroots-level data collection.	commercial conductivity sensors, especially under complex or high ionic strength conditions.
7	Conducted a laboratory comparison of commercial and open-source EC sensors. Tested their accuracy and precision using standard solutions under controlled conditions.	Commercial sensors exhibited superior accuracy and precision. Open-source options were cost-effective and customizable for specific applications.	Open-source sensors lacked reliability for highly precise or regulatory applications; commercial sensors involved high acquisition costs.
8	Introduced "SensorTalk," an algorithm for optimizing EC sensor operating cycles to extend sensor life. Focused on hardware integration and predictive maintenance techniques.	Prolonged sensor durability and reduced operational costs, enhancing system reliability and reducing environmental waste from redundant sensor replacements.	Implementation challenges with existing infrastructure require expertise to develop and maintain the predictive maintenance framework.
9	Developed an optimal control algorithm for fertigation systems based on real-time EC sensor feedback, integrating nutrient delivery adjustments in greenhouse environments.	Improved crop yields and reduced resource waste by fine-tuning fertigation based on precise EC feedback, demonstrating significant optimization in controlled environments.	Complex implementation requires advanced calibration and robust sensor systems, which is challenging for operators without specialized technical knowledge.
10	Implemented a fertigation system with soil moisture and electrical conductivity sensors. Used controlled-release fertilizers and sensor feedback to optimize water and nutrient delivery.	Increased yields and reduced environmental impacts by delivering nutrients and water precisely based on real-time soil feedback.	The high initial cost of sensor systems and controlled fertilizers requires technical knowledge for practical use.
11	Designed "FishTalk," an IoT-based aquarium system with pH, temperature, and dissolved oxygen sensors. Real-time data was processed and transmitted to a mobile app for monitoring and control.	Enhanced fish health and simplified aquarium management through automated monitoring and real-time adjustments.	Initial setup complexity and cost may deter hobbyists and potential technical challenges for non-technical users.
12	Machine learning models with electrical conductivity and pore-water sensors were used to optimize nutrient delivery in soilless tomato cultivation, integrated interpretable ML techniques for actionable insights into nutrient dynamics.	Improved crop yields and sustainability by optimizing fertigation through advanced data-driven techniques.	Extensive training data is required for the ML model; system complexity may pose a barrier to widespread adoption.
13	Implemented an automated fertigation and irrigation system using soil moisture, electrical conductivity, and environmental sensors. The system dynamically adjusted water and nutrient delivery based on real-time sensor data.	Increased water and nutrient use efficiency, reduced labour requirements, and improved yields.	High setup costs and complexity require skilled operators to troubleshoot and maintain the system.

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14	Designed an IoT-enabled water quality monitoring system for greenhouse irrigation, utilizing multi-parameter sensors (pH, EC, turbidity) linked to a cloud-based platform.	Optimized water and nutrient management, minimizing waste and maximizing crop productivity through real-time monitoring and automated adjustments.	Expensive initial setup; dependent on reliable internet connectivity and skilled personnel for system operation and troubleshooting.
15	Developed equations for ionic molal conductivity and coupled them with geochemical speciation models. Validated with 1,593 water samples.	High accuracy in conductivity predictions (±0.7% mean difference). Identified major contributors like Na+ and Ca2+.	Limited by predefined ions and geochemical models. Accuracy depends heavily on water chemistry quality and is computationally intensive.
16	Designed an Arduino-based system with EC probes and thermistors to evaluate the relationship between EC and temperature in synthetic seawater.	Confirmed a linear relationship between EC and temperature. The system provided an affordable, replicable educational tool for water quality studies.	Limited to controlled experimental conditions. Requires validation in real-world settings. Accuracy depends on sensor specifications.
17	Reviewed traditional (gravimetric) and remote sensing (RS) methods for TDS and TSS measurement. RS methods employed UAVs and satellite imagery with deep learning and machine learning models.	Highlighted the effectiveness of RS for large-scale monitoring—improved spatiotemporal resolution through data fusion and advanced algorithms.	RS methods face challenges like atmospheric interference and require integration with traditional techniques for validation and calibration.
18	Developed constant coefficients for TDS prediction from EC in two Iranian experimental areas using regression models and statistical analysis.	Achieved high correlation coefficients (0.977 & 0.997) between TDS and EC. Provided robust coefficients for predicting TDS from EC in specific contexts.	The context-specific coefficients may not generalize to other regions or chemical compositions.
19	Reviewed TDS and EC correlation studies, emphasizing the impact of ion types and water salinity. Used historical data and experimental results.	Validated the dependency of TDS/EC ratios on ionic composition and water salinity. Reinforced the importance of calibration for accurate TDS prediction.	Limited applicability for waters with varying or complex ionic compositions.

On these very bases, our research focuses on advancing a relatively low-cost but highly accurate EC sensor. Incorporating advanced calibration technology while taking full advantage of IoT connectivity, such a sensor will present high-accuracy real-time measurements under various agricultural conditions. Thus, it aims to close the gap between affordability and precision and, therefore, ensures the generation of reliable data for better crop management and sustainability. That way, agricultural practices are redefined by providing an economical and practical tool for monitoring water quality, which benefits farmers and the agricultural sector. Taken together, this work aims to design and fabricate the EC sensor for water quality measurement with IoT development. Then we analyze and compare the collected data to identify patterns related to the EC sensor performance. In the end, we evaluate the EC sensor performance under various environmental conditions and water quality parameters.

METHODOLOGY

In this section the detailed process used to design and evaluate the proposed EC sensor are discussed. It involves hardware design and software configurations, numerous testing and measurements.

The process begins by evaluating existing on the shelf total dissolved solids (TDS) sensor with DS182B temperature sensor, calibration of the TDS sensor and EC Meter from Hanna Instruments. The characterization of the DF Robot TDS sensor is performed, and the proposed design of electric circuits is explained.

Evaluation of existing Total Dissolved Solids (TDS) sensor with DS182B temperature sensor

The DF Robot TDS Sensor [20] is used to monitor water quality, providing reliable measures for TDS. The sensor is commonly used in hydroponics, aquaponics, and water purification systems. It works on both Arduino and other microcontrollers. The key specifications of the DF Robot TDS Sensor are summarized in Table 2, which outlines essential parameters such as operating voltage, measurement range, output signal type, and accuracy, providing a comprehensive overview of the sensor's capabilities.

The DF Robot TDS Sensors have been proven applicable in many fields. Hydroponics and aquaponics estimate nutrient solutions and accomplish their suitable growth conditions for plant and aquatic environments. The sensor can also test the appropriate conditions of drinking water, aquariums, and swimming pools for purity and safety in case of water quality monitoring. It is also essential to the industries about quality control processes in water treatment plants as they comply with standards according to the regulatory authorities.

Table 2. The key specifications of the DF Robot TDS sensor.

Parameter	Value
Model Number	SEN0244
Supply Voltage	3.3V-5V
Output Signal	Analog Voltage
TDS Measurement Range	0-1000PPM
Compatible Microcontrollers	Arduino, ESP32, Raspberry Pi
Probe Material	Stainless Steel
Dimension	Sensor module: 42mm x 32mm x 8mm

A temperature sensor, DS18B20 is used together with the TDS sensor. DS18B20 is a high-performance temperature-measuring digital sensor used mainly for its accuracy and simplicity. Its measurement range is -55°C to +125°C with an accuracy of ±0.5°C for -10°C to +85°C. This sensor works with just a single wire for data communication with a microcontroller, and it needs power and ground lines.

The key features of a DS18B20 temperature sensor include programmable resolution from 9 to 12 bits, the ability to connect many sensors in one data line, and built-in non-volatile memory to record user-defined settings. Its small size and very good performance are thus appropriate for such applications as environmental monitoring, HVAC control systems, and industrial control.

Schematic circuit of TDS and temperature sensors

The schematic circuit of the DF Robot TDS sensor is implemented with an Arduino Uno microcontroller and

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a temperature sensor as shown in Figure 1. Analogue signals are output from the TDS sensor to Arduino for processing, while the temperature sensor provides compensation data for the TDS measurement's accuracy.

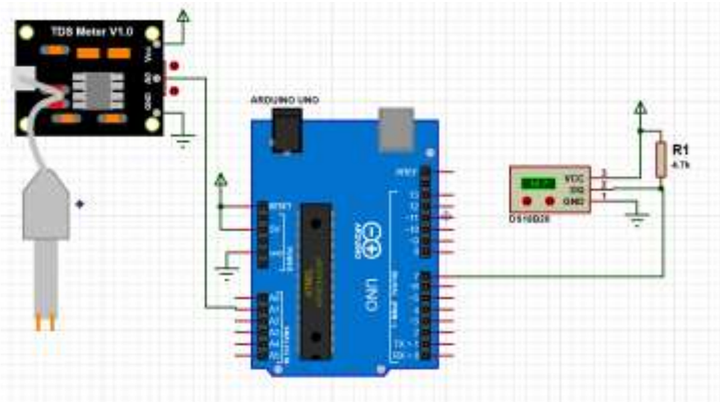

Figure 1. The schematic circuit of the sensor system

This illustrates the schematic circuit for the system. The DF Robot TDS sensor circuit consists of three connection points: the "+" connects to the 5V power supply, the "-" connects to the GND, and the "A" connects to the A1 analogue pin on the Arduino. The temperature sensor that is being used is DS18B20, where the DAT or DQ pin is connected to the digital pin 7 on the Arduino through a resistor in series and then to the VCC, and the VCC pin of the temperature sensor is connected to the VCC and GND to the ground. This setup ensures that the measurement of TDS is accurate with temperature compensation.

Calibration of TDS sensor and EC meter

The first one to start with is to calibrate the sensor so that it produces gravitational readings as shown in Figure 2. From the point of calibration, error-correcting reference points become appropriate for adjusting deviations from actual measurements caused by factors related to the environment or device. Immersing the sensor probe into a solution of known TDS value serves as a dip calibration; adjust the sensor setting until the displayed reading conforms to the reference, then verify calibration against the second standard device if necessary. The performance will thus be accurate and repeatable. The TDS in PPM can be calculated from the EC in µS/cm with the formula $TDS = \frac{EC \times 1000}{2}$ for TDS values in PPM. This is an approximate formula to convert EC values into a relationship regarding electrical conductivity and concentration of dissolved solids in the water. For example, a calibration solution of 1,413 µS/cm EC produces 706 PPM of TDS at room temperature ($25°C$), suitable to the range of 0-1000 PPM operationally for the DF Robot sensor.

Figure 2. TDS DF robot probe in standard electrical conductivity solution

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Typically, calibration using the EC meter is reliable and relatively accurate in measuring conductivity. Here as shown in Figure 3, it uses mainly a conductivity standard of 12,880 μS/cm supplied by Hanna Instruments. Since the standard's conductivity is temperature-dependent, it would be appropriate to consider the temperature variation using the results from the temperature-conductivity chart that comes with the standard solution. The solution is allowed to mix by stirring gently while avoiding introducing air bubbles. The temperature of the sample is measured, and then it is possible to cross-reference the temperature-conductivity to obtain conductivity values from the standard chart. It is then set for calibration on the Hanna EC meter, and the probe is fully submersed in the standard solution with no air trapped in it.

Figure 3. **EC Hanna meter in standard calibration solution**

After immersion, the meter should be allowed to stabilize for comparison and adjustment through the calibration controls should the displayed value deviate from the reference conductivity. A final calibration confirmation can be done by rinsing the probe with distilled water and then re-immersing it in the standard solution to verify the same readings recorded during calibration. It includes recording calibration data like the date, time, temperature of the solution, and the last adjusted value for traceability purposes. Storing an EC meter and probes per the manufacturer's instruction will ensure that the EC meter's final accuracy and long life are maintained even after calibration. In this regard, systematic calibration ensures that the EC Hanna meter measures correctly in terms of conductivity recording, making it reliable for any experiment or analytical work.

Characterization of the DF Robot TDS sensor

The TDS measurement system was characterized by using an Arduino Uno as depicted in Figure 4 to evaluate the performance of the DF Robot TDS sensor concerning its temperature compensation capabilities. The DF Robot TDS sensor was connected to the analog input pin A1 of the Arduino Uno, and a DS18B20 digital temperature sensor was used and connected to digital pin 7. The temperature compensation for the TDS calculation used the following formulas:

Temperature Compensation Coefficient: = 1.0 + 0.02×(temperature-25°C)

Compensated Voltage = (average voltage)/(compensation coefficient)

TDS Value = (133.42 ×CompensationVoltage^3 - 255.86×CompensationVoltage^2

+ 857.39 ×CompensationVoltage) × 0.5

Comparison of TDS values measured using Arduino Uno with EC values recorded using the Hanna EC meter paved the way for an equation to convert TDS values obtained from the DF Robot sensor into their corresponding EC equivalents. The collected data and subsequent analysis have confirmed the accuracy of the

DF Robot TDS sensor for TDS measurement, aided by the formula for temperature compensation inaccurate readings. The conversion equation given is a way to convert the readings from the TDS sensor into a standard likely EC value from the Hanna meter.

Figure 4. TDS DF robot and temperature with Arduino Uno Proposed circuit design

Figure 5 shows the block diagram of the proposed circuit and system. The system uses IoT-integrated EC sensors to monitor water quality in real-time. This makes it possible to remotely and continuously monitor the quantities of dissolved ions in irrigation water, which is an essential function for controlling salinity and water quality. The system enables accurate fertigation strategy modifications through fast data provision, guaranteeing adequate nutrient delivery and mitigating the risk of salinity-induced crop damage. This real-time monitoring improves crop health and productivity by keeping the proper ratio of salts and nutrients in place.

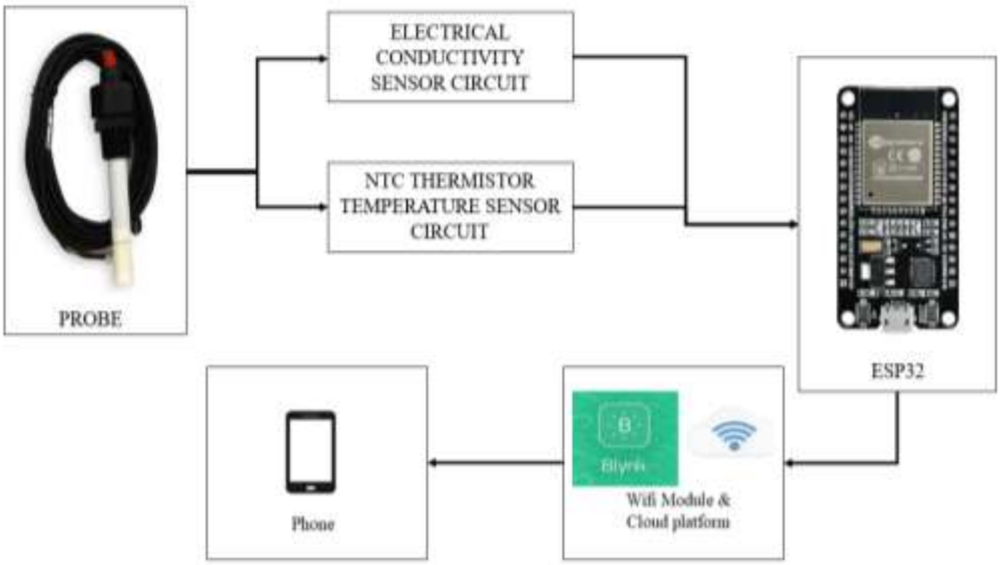

Figure 5. Block diagram of the proposed circuit design

At the very beginning part of the project, an EC sensor and a temperature sensor circuit will be connected to the microcontroller known as the ESP32. These sensors will measure the temperature and electrical conductivity of the water. These sensors' signals will go via the appropriate circuits for processing and amplification. The analogue ports of the microcontroller will receive the analogue voltage signals, which have a range of 0-3.3V. The sensor data will be read by and processed by the ESP32 microcontroller. The project will also evolve into an Internet of Things (IoT) system. One benefit of the ESP32 is that it has an integrated Wi-Fi module. The gadgets will be connected to the Internet of Things via the Blynk platform. By including IoT in the programming, system data and parameters, including output voltage and water quality level, will be

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displayed and viewable on a smartphone or web page. This makes it possible to monitor water quality remotely and make timely modifications to maintain the best possible quality for agricultural usage.

Schematic circuit of the proposed design

The measurement of total dissolved solids (TDS), expressed in milligrams per liter (mg/L) or parts per million (ppm), is essential in water treatment, agriculture, and environmental monitoring. Accurate TDS measurement relies on electronic devices capable of detecting and processing the electrical signals generated by TDS sensors submerged in water. Signal conditioning is a critical step in this process, involving filtering, amplifying, and processing these signals to ensure precision. Operational amplifiers (op-amps) are commonly used in signal conditioning circuits to provide gain, filtering, and impedance matching.

A TDS measurement system typically comprises several key components, including an oscillator, rectifier, negative voltage generator, AC amplifier, TDS probe, and signal conditioning stages. Each element plays a specific role in enhancing system accuracy and performance by processing the electrical signals from the TDS probe into a usable form for further analysis.

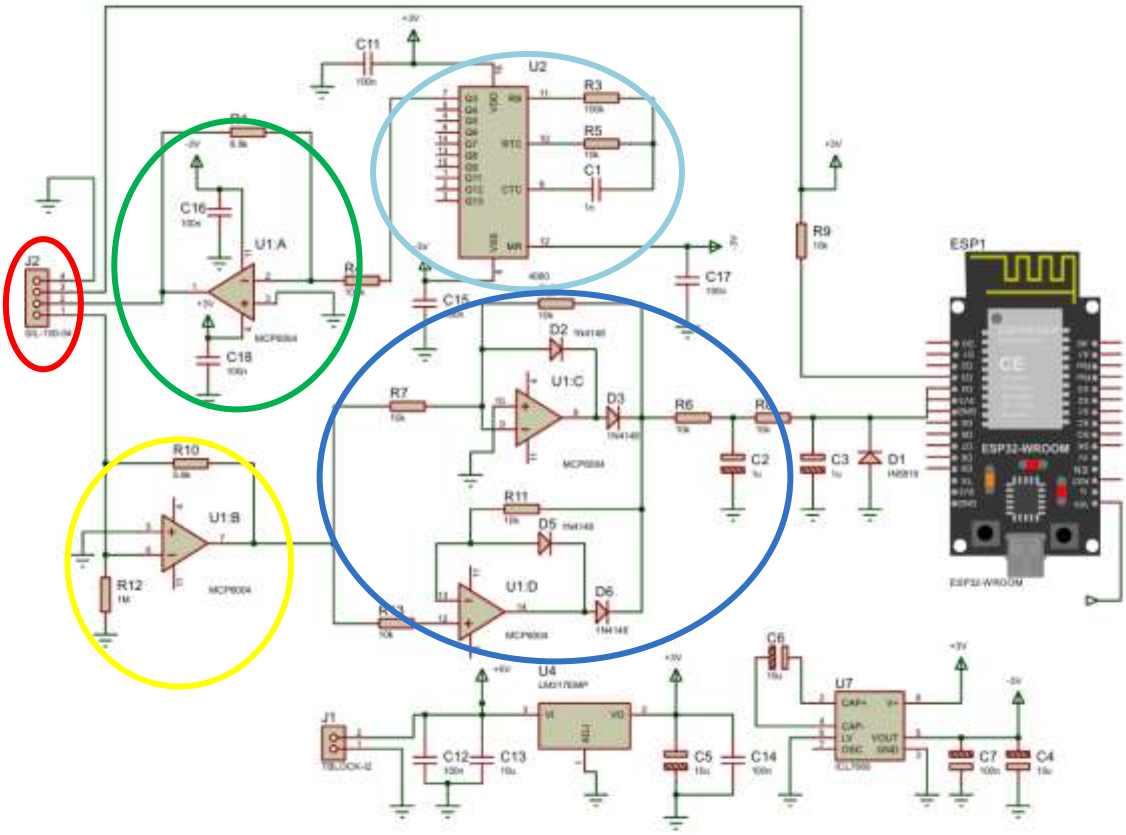

Figure 6. Schematic circuit of the proposed design

Figure 6 shows the schematic circuit of the proposed TDS sensor. The explanation of main components of the circuit is as follows:

Probe (Input) (red circle):

The probe is one of the most effective tools that could be used in water quality monitoring. Generally, it measures the electrical conductivity of a liquid and then calculates the concentration of particles that are dissolved in it. Typically, it has two electrodes immersed in a fluid or a combination of liquid and gas. In the presence of dissolved solids, conductivity increases with the increase in the number of dissolved solids. There are various planned conversions from observed conductivity to TDS, and calibration is required as the relationship between conductivity and TDS is not linear. Some of these variables are temperature, ionic concentrations, and the composition of the electrode material [20]. Figure 7 shows the TDS and temperature sensor probe used in this work.

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Figure 7. Probe for TDS and Temperature

Oscillator (purple circle)

Oscillators are widespread components in electrical circuits, especially those that involve time or signal generation. This part generates an oscillation at a specific frequency, which may be a square pulse or sine wave. In the context of the entire system, the oscillator is most frequently involved as a clock or reference signal to coordinate the device's timing for various operations or measurements. The timing and the synchronization: For the circuit to function correctly, there is a requirement for time, which is when the oscillator comes to the rescue as it delivers a stable and accurate frequency signal.

AC Amp (green circle)

The preferred circuit, the AC amplifier, further enhances the signal generated by the Signal Conditioning Block. This amplification procedure is needed to increase the signal's intensity to levels suitable for further processing. The AC amplifier could also have processing options such as filter and gain. The select assists in rejecting noise and interference incorporated in the signal, while gain modifies assist in perfectly fashioning the amplification feature. These qualities also enhance signal processing by minimizing interference and noise, improving the signal-to-noise ratio.

Signal Conditioning Block (yellow circle)

Using a probe, an electrical signal that determines the conductivity of the liquid is also measured in the Signal Conditioning Block. This block prepares the signal for further procedures in the chain. The two primary mechanisms that can be used for this purpose are voltage scaling and impedance matching. A voltage divider circuit is also used to scale down a voltage signal to the desired and proper voltage level required by the other subsequent components. Such a buffer can also match impedance, making the signal transmitted to the next level efficient and without loss. Signal conditioning plays a crucial role in amplifying and shelving the subsequent measurements or analyses while protecting the signal's integrity.

Rectifier (blue circle)

It isolates the direct current (DC) signal from the alternating current (AC) signal produced by the AC amplifier. For this purpose, an AC voltage is often applied to diodes in circuits like the full-wave or half-wave rectifier. It also allows for rectifying a signal and ensures that the output is unidirectional in later stages of operation. Accordingly, given the application requirement, the corrected DC signal may be used as is or further processed.

RESULT AND DISCUSSION

In this section, data from the experiment, including TDS and EC measurements and integration with the Blynk IoT system are analyzed. We provide the prototype of the proposed sensor circuit. This section also presents the outcomes of the TDS and EC measurement system, including the readings' accuracy, reliability, and overall performance.

Prototype of the proposed TDS and EC sensor circuit

Printed Circuit Boards (PCBs) are essential components of electronic systems, comprising a board with copper traces and attached components to conduct current through the circuit. PCBs were designed as the hardware for this project. Figure 8 illustrates the finalized circuit for the entire project.

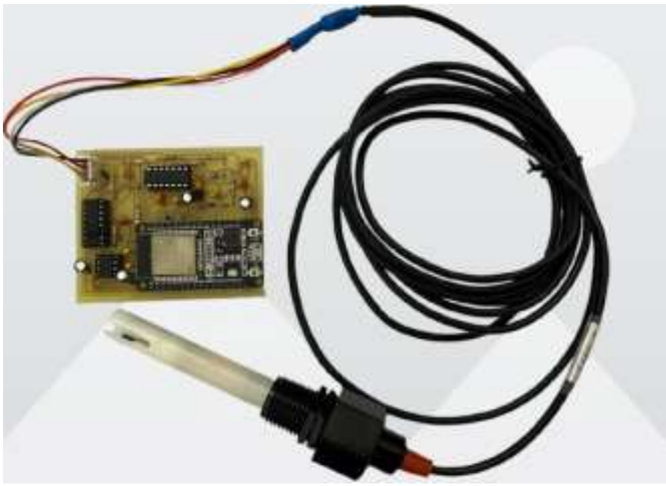

Figure 8. The whole project circuit after modification.

This circuit takes readings alongside a Hanna EC meter for comparisons and validations. The Serial Monitor reads TDS, temperature, and EC values for functionality testing and Blynk IoT cloud reports through Wi-Fi for real-time monitoring and diagnostics. This arrangement ensures accurate and current measurement results over the Internet.

Characterization of proposed circuit design with EC meter

An experiment we conducted to analyze the relationship between electrical conductivity (EC) and total dissolved solids (TDS) using the proposed circuit design matched with the Hanna EC sensor as shown in Figure 9 and Figure 10. The conducting capacity of a solution is one major factor in determining how this sensor evaluates the water status. This involves salinity and the concentration of dissolved minerals in the water. It is an important measurement as it directly correlates with the million-dollar question of water quality- high conductivity, more salinity, or dissolved solids.

The dissolved solids were based on the DF Robot TDS sensor principle to measure conductivity, which is further converted to TDS values. On the other hand, the proposed circuit design measures electrical conductivity (EC) using the proposed circuit design and Hanna EC sensor, intended to be built and analyzed to develop the test circuit that measures the relationship between total dissolved solids and electrical conductivity. This means that the readings from such sensors will be in ppm and mS/cm (respectively) and are calibrated with the usual standards for accuracy. The whole experimental setup, therefore, lays down the foundation to describe the evolution of the proportional relationship between EC and TDS, which could further analyze how the change in water composition affects conductance and dissolved solids, ultimately leading to an assessment of water quality.

It's a single-board integrated design circuit incorporating a TDS and temperature sensor. Incorporating an analogue output sensor measuring temperature into the TDS because these temperature readings enable a more precise compensation of TDS calculations according to temperature variations. The two measures become a unit, an installation that is more useful and reliable.

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Figure 9. The designed circuit together with EC meter

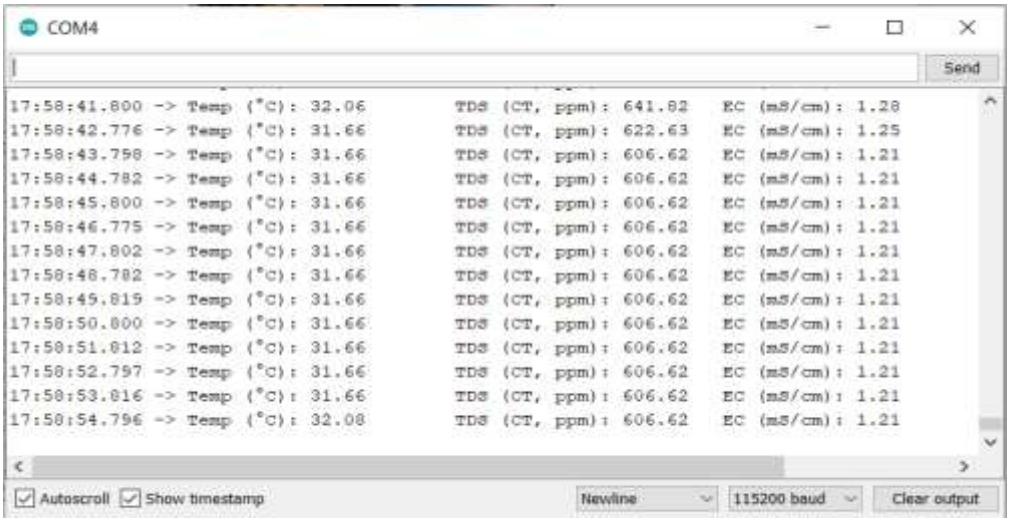

Figure 10. The output of the proposed circuit in serial monitor

The indicated differences observed in the above figures would be because of found PPM values from the proposed design and those calculated ones from the Hanna EC sensor because differences could arise due to calibration differences between sensors, precision differences in measurement, or innate differences in different ways in which sensors measure conductivity and dissolved solids. This results in better insight into the relationship and the discrepancy between the two measurement systems for further improvement and validation of the proposed design circuit accuracy and reliability. Table 3 shows the differences between the TDS values of the new circuit and those derived from the Hanna sensor. This research aims to find an equation that matches this reading in all ranges with the Hanna sensors to maintain consistency and accuracy on all concentrations tested.

Table 3. EC and TDS value of the proposed circuit and Hanna Meter

HANNA			Proposed Circuit		
EC (mS/cm)	TDS (PPM)	˚C	EC (mS/cm)	TDS (PPM)	˚C

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0.13	65	29.4	0.00	0	29.87
0.21	105	29.3	0.06	29	30.47
0.35	175	29.3	0.18	93	30.5
0.46	230	29.4	0.27	139	30.5
0.6	300	29.4	0.38	194	30.5
0.7	350	29.4	0.45	229	30.5
0.84	420	29.4	0.56	285	30.5
0.93	465	29.4	0.61	319	30.5
1.07	535	29.4	0.74	375	30.5
1.18	590	29.4	0.82	415	30.5
1.33	665	29.4	0.93	477	30.5
1.43	715	29.4	1.04	538	30.5
1.58	790	29.4	1.21	610	30.5
1.68	840	29.4	1.31	663	30.5
1.84	920	29.4	1.47	748	30.5
1.93	965	29.4	1.62	818	30.5
2.08	1040	29.4	1.84	924	30.5
2.17	1085	29.4	2.00	1007	30.5
2.33	1165	29.4	2.17	1095	30.5
2.41	1205	29.4	2.29	1161	30.5

Figure 11 shows how the data form was segmented into three concentration ranges for analyzing the observed and recorded nonlinear variation as influenced by varying levels of the concentration of the solution. A linear equation for each range was fitted to the data using the `polyfit' function, which determined the slope and intercept for their best-fit lines.

This segmentation was understood to be a sharp and perfect calibration between the reading of the new circuit and the Hanna sensor independent of the concentration level. The goodness of fit for each linear model was represented as R^2 value, yet another testimony of the exactness of this kind of perspective. The graph was designated to show the original blue points connected by lines within the original datasets, while segmentation linear fits were indicated with bold dashed lines with different colors. Equations of each segment and the R^2 value displayed on the graph would be used to validate the calibration method. This way, dissection into linear segments has helped render a very accurate correlation of the circuit readings to the calibration environment and made the reading reproducible by compensating variations in response caused by variations in concentration.

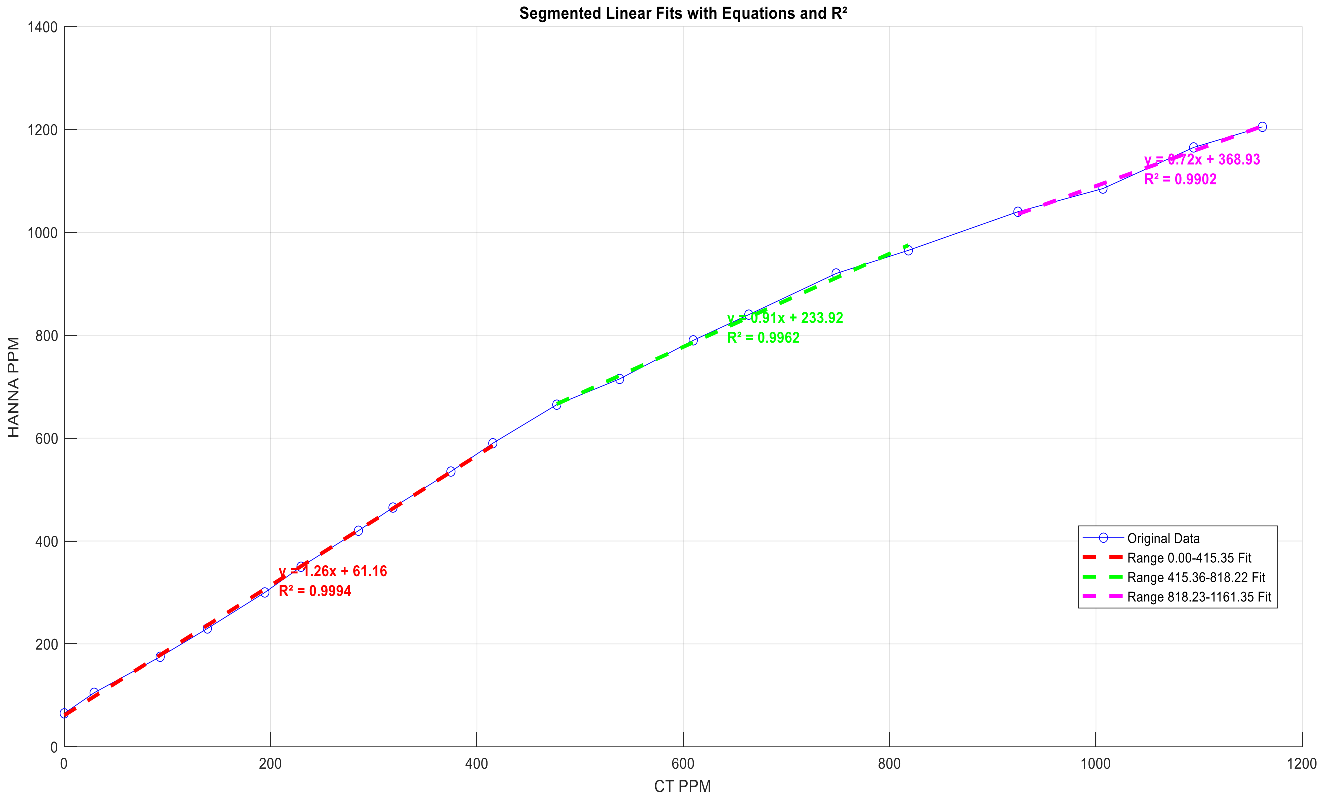

Figure 11. The graph of linear data from the proposed circuit with Hanna Meter

Figure 12 shows an example of Blynk Dashboard for the IoT system. The ESP 32 microcontroller will communicate with Blynk Dashboard to display the current readings from the sensors.

Figure 12. Sensor reading in Blynk Dashboard

Table 4 presents the equations derived from the linear graph, corresponding to different ranges of raw TDS values. These equations convert raw TDS readings from the new circuit into more accurate TDS values aligned with the Hanna sensor.

Table 4. Equation of the linear data

NO.	Range of Raw TDS (PPM)	R^2	Equation (PPM)
1	0.00 to 415.35	0.9994	$TDS = (1.2622 \times Raw\ TDS) + 61.1641$
2	415.36 to 818.22	0.9962	$TDS = (0.9057 \times Raw\ TDS) + 233.9192$
3	818.23 to 1161.35	0.9902	$TDS = (0.7211 \times Raw\ TDS) + 368.9319$

These equations were implemented in the Arduino code for the proposed design. The code chooses an appropriate equation particular to the measured range of raw TDS values to allow for proper calibration and conversion for each one of these measurements.

Table 5 shows the data taken after applying the three linear equations from the previous table.

Table 5. Sensor data taken after applying the three linear equations

HANNA			Proposed circuit		
EC (mS/cm)	TDS (PPM)	˚C	EC (mS/cm)	TDS (PPM)	˚C
0.12	60	28	0.12	62	28.25
0.23	115	28.1	0.23	113	28.48
0.3	150	28.1	0.31	153	28.5
0.4	200	28.1	0.40	201	28.48
0.53	265	28.1	0.53	266	28.48
0.65	325	28	0.66	330	28.37
0.77	385	28	0.77	383	28.41
0.87	435	28	0.87	433	28.37
0.97	485	28.1	0.97	483	28.45
1.13	565	28.1	1.13	566	28.31
1.24	620	28.1	1.24	621	28.37
1.35	675	28.1	1.35	675	28.43
1.47	735	28.1	1.47	733	28.23
1.59	795	28.1	1.59	795	28.27
1.7	850	28.1	1.71	853	28.27
1.84	920	28.1	1.84	921	28.2
1.95	975	28.1	1.95	974	28.33
2.05	1025	28.1	2.01	1004	28.29

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In short, the table above compares the global values of EC, TDS, and temperature between the Hanna sensor and the new circuit, with minimal discrepancy between the two. The following table notes that the difference is between the error values recorded by the new circuit and Hanna sensor readings, thus generating more detail related to the accuracy and reliability of the new circuit.

Table 6. show the data error after applying the three linear equations from the previous table.

Table 6. Comparison between the Proposed EC circuit and reading from EC meter

EC HANNA (mS/cm)	**EC Proposed Circuit** (mS/cm)	**ERROR**
0.12	0.12	0.00
0.23	0.23	0.00
0.3	0.31	-0.01
0.4	0.40	0.00
0.53	0.53	0.00
0.65	0.66	-0.01
0.77	0.77	0.00
0.87	0.87	0.00
0.97	0.97	0.00
1.13	1.13	0.00
1.24	1.24	0.00
1.35	1.35	0.00
1.47	1.47	0.00
1.59	1.59	0.00
1.7	1.71	-0.01
1.84	1.84	0.00
1.95	1.95	0.00
2.05	2.01	0.04

The table shows the error values between the Hanna sensor's EC readings and the proposed circuit. The errors are generally relatively small; most show no deviation or a -0.01 mS/cm difference. An exception is the EC value of 2.05 mS/cm, which has a slightly higher error at 0.04 mS/cm.

The reason for this more significant error is that the proposed circuit can read up to very close to 1000 ppm or approximately 2.0 mS/cm. Above that range, the measurement accuracy of that circuit declines and results in a more significant error variance from the reading of the Hanna sensor. Such an inherent limitation requires modifications or enhancements in the circuit for concentrated measurements

However, in Figure 13, the errors do not affect the graph. So, from the graph, the results of the Proposed Circuit Design are very close with the EC Hanna meter.

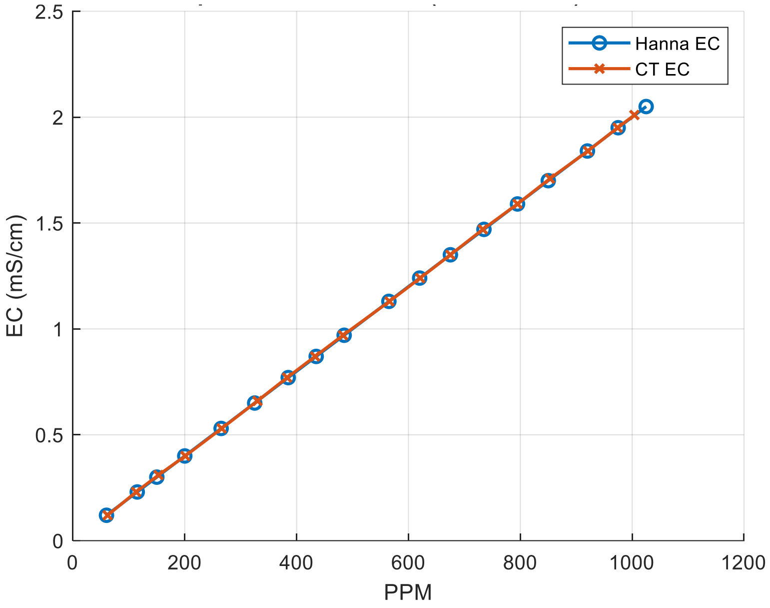

Figure 13. Graph of the final EC Hanna and EC New Circuit

Figure 14 presents the graphs between the EC (in mS/cm) and TDS (in ppm) for the Hanna EC sensor, the proposed circuit, and the DF Robot TDS sensor.

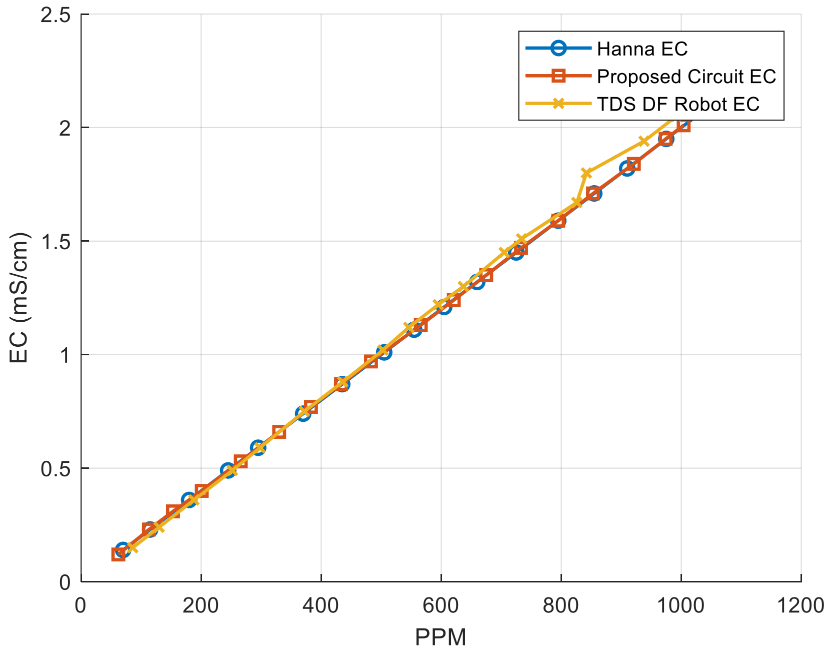

Figure 14. Comparison of three EC data

As depicted in the graph, all three correlate near-linearly, with the proposed circuit mirroring the Hanna EC readings almost precisely. The TDS DF Robot sensor shows fair agreement along the range, but slight discrepancies toward the higher TDS end reflect its calibration quality. In contrast, the proposed circuit followed the Hanna EC for the whole range, confirming its viability as a reliable and very accurate device for EC measurements. Hence, it further emphasizes integrating the proposed circuit with temperature compensation to improve the measurement.

Based on the results from the Hanna EC sensor, TDS DF Robot sensor, and proposed circuit design, there is a good linear relationship between Electrical Conductivity and Total Dissolved Solids. All three systems give closer type values at lower TDS levels, suggesting that the TDS DF Robot and the proposed circuit give reliable measurements in this region. In higher TDS measurements, the systems tend to diverge quite a bit at a very low degree, but not to the DF Robot, which often shows a small quantity of upward drift to the Hanna EC sensor. This was ascribed to the DF Robot's inability to calibrate and its environment's sensitivity, such as temperature changes that are not compensated in its standalone mode.

On the other hand, the proposed circuit design gives reasonably accurate results throughout the whole TDS range in close approximation to the Hanna EC sensor due to the circuitry's temperature compensation mechanism that considers these changes in water temperature, a critical parameter for accurate measurement. The proposed error limits of the design ranged from -0.01 to 0.04 mS/cm. Therefore, it can be used as consistent and reliable data to support the soundness of the calibration procedure used. These results testify to the robustness of the proposed circuit for practical use where high-precision measures of EC and TDS are needed regardless of changing conditions.

CONCLUSION

In this paper, we have developed an electrical conductivity (EC) sensor circuit using a TDS sensor probe. The proposed prototype is capable of measuring the total dissolved solids (TDS) concentration in water and converting it into EC values with good accuracy. Experimental comparisons with the existing DF Robot TDS sensor and a commercial-grade Hanna Instruments EC meter demonstrated that the proposed circuit produces reliable and accurate TDS and EC measurements comparable to commercial products. The developed EC sensing system provides a cost-effective and practical solution for continuous water quality monitoring, where EC serves as one of the key indicators of dissolved ionic content, salinity, and overall water quality. Continuous monitoring of EC enables the early detection of water contamination, changes in mineral concentration, and abnormal water conditions, making it suitable for applications such as drinking water monitoring, irrigation systems, aquaculture, wastewater treatment, and industrial process control.

Furthermore, the proposed EC sensor contributes directly to the achievement of the United Nations Sustainable Development Goal (SDG) 6: Clean Water and Sanitation, particularly by supporting Target 6.3, which aims to improve water quality through pollution reduction and enhanced monitoring of water resources. The availability of a low-cost and accurate EC monitoring system also supports SDG 9: Industry, Innovation and Infrastructure by promoting innovative sensing technologies for smart environmental monitoring and digital water management systems. In addition, the ability to continuously monitor water quality encourages efficient water resource utilization and pollution prevention, thereby contributing to SDG 12: Responsible Consumption and Production through more sustainable water management practices.

Future work should focus on refining the calibration process using a wider range of certified standard solutions to improve measurement consistency across different conductivity levels. Further improvements can also be achieved by implementing more advanced temperature compensation algorithms, enhancing sensor sensitivity, and incorporating automatic calibration techniques to reduce measurement errors, particularly at higher conductivity ranges. Integration of the proposed EC sensor with Internet of Things (IoT) platforms and cloud-based monitoring systems could further enable real-time water quality surveillance, remote data access, and predictive maintenance. These enhancements would improve the accuracy, reliability, and long-term stability of the system, making it suitable for deployment in smart water management applications that support sustainable environmental monitoring and the achievement of the UN Sustainable Development Goals.

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