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# Low-cost continuous measurement system to learn the relationship between electrical conductivity and temperature in brackish waters

F.A. Leon[a,*], A. Ramos-Martín[b], C. Mendieta[b]

[a]*Institute of Intelligent Systems and Numerical Applications in Engineering (SIANI), Universidad de Las Palmas de Gran Canaria, Campus de Tafira 35017, Las Palmas G.C., Spain, Tel. 00 34 686169516; email: federico.leon@ulpgc.es*
[b]*Department of Process Engineering, Universidad de Las Palmas de Gran Canaria, Spain, emails: alejandro.ramos@ulpgc.es (A. Ramos-Martín), carlos.mendieta@ulpgc.es (C. Mendieta)*

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**ABSTRACT**

This work proposes the use of inexpensive experimental equipment to allow engineering students and professionals to observe and deepen their understanding of the different relationships between water quality parameters. In the case considered in this work, the experimental equipment is designed to observe and enable an understanding of the relationship between the electrical conductivity (EC) of brackish water and its temperature (T). The experimental design includes an embedded Arduino Nano microcontroller system. Importantly, the design is based on flexible and open-source software and hardware, facilitating its modification for other related studies. In this work, the effect of T on the EC of sodium chloride and potassium chloride solutions at different salinities was determined. A mixture of these two salts with magnesium chloride to represent the main components of seawater was also studied. It is shown that the relationship between T and EC, at different concentrations of the salts, fits a linear model which includes different equations resolved with the data taken during the empirical study. EC conductivity is a measure of the current conducted by ions present in the water (phenomenon of conductors of the second kind) and depends on the concentration and nature of the ions and the temperature and viscosity of the solution, as reported in ISO 7888-1985.

*Keywords:* Electrical conductivity; Reverse osmosis; Water quality; Embedded systems

## 1. Introduction

This article presents an idea for a low-cost experimental design to allow students to gain insights into the relationship between the electrical conductivity (EC) of brackish water and its temperature (T). The design, which includes an embedded Arduino Nano microcontroller system, is principally characterized by its versatility in tackling different problems and by the use of free and open-source tools in terms of computer applications, components and the elements used. Importantly, this latter aspect enables economically feasible modifications of the design depending on the future needs of students or teachers. In the present study, several series of tests were implemented with different types of salts common in brackish water at different temperatures. Following ISO 7888-1985 on water quality and EC determination, suitable methods were employed in the design to observe how the EC of the solutions varies with T and the type of salt used. The proposed design can be used to understand and learn how to achieve the objective of obtaining the relationship between EC and T as a linear fit.

Given the considerable complexity in the relationship between the EC, the amount of total dissolved salts (TDS) and the T of the water to be treated in reverse osmosis

* Corresponding author.

plants [1–3], it is of interest to design learning strategies that help students, in the field of water treatment, observe and deepen their understanding of the relationships between these variables. Such learning strategies can be based on the use of experimental or laboratory artifacts or designs related to the study and analysis of the above questions [4,5].

The main topics dealt with in this paper are the following:

- The complexity of the relationship between the EC, the amount of TDS and T of water to be treated in reverse osmosis plants.
- The design of learning strategies, based on information and communications technology (ICT), helps students in the field of water treatment to observe and deepen their understanding of these relationships.
- These learning strategies could be based on the use of experimental artifacts or designs, designed specifically for the study and analysis of the above.
- The latest educational proposals are based on theories of psychological learning – through the use of adequate learning environments in line with the constructivist approach to learning through active techniques.
- These artifacts can be presented in the form of prototypes, where it is possible to use low-cost embedded systems, enabling considerable versatility in experimental design and allowing engineering students to observe and deepen their understanding of the relationship between the EC and T of brackish water.

## 2. Material and methods

To carry out the proposed assessment of the relationship between EC, T and TDS, a continuous measurement system of the variables was designed based on an embedded microcontroller system and a series of transducers. The system, shown in Fig. 1, was used in a study (conducted from early 2016 to 31 January 2017) to explain the effect of T on the EC of sodium chloride and potassium chloride solutions at different salinities.

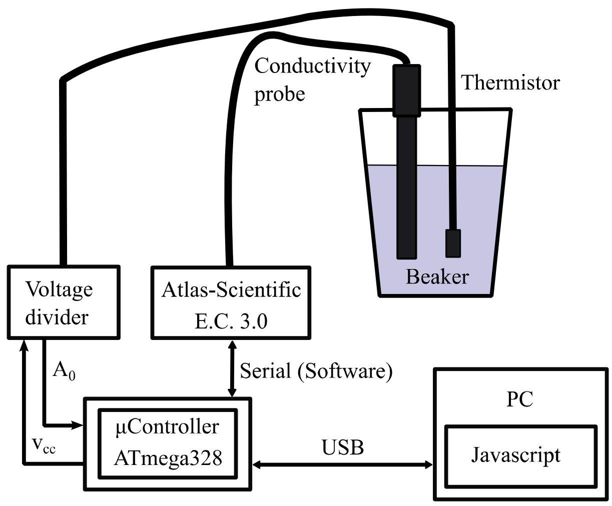


Fig. 1. Low-cost system to measure electrical conductivity (EC) and temperature (T).

Importantly, the design is based on flexible and open-source software and hardware, allowing its modification as required by students. More specifically, the equipment, material and apparatus used (Fig. 1) are as follows:

- An Atlas Scientific EC probe with graphite surface and measuring range between 5 and 200,000 µS/cm.
- A submersible NTC thermistor with stainless steel housing. A voltage divider for estimation of the resistance value of the thermistor, using the measurement of the voltage of the divider, which is related to the temperature reached by the transducer, in thermal equilibrium with the solution. The thermistor resistance is A0 and the supply voltage is Vcc.
- An ATmega328 (Atmel) microcontroller implemented in an embedded system, named Arduino Nano (Arduino), responsible for controlling the measurement processes of communication with the EC probe circuit and of the voltage divider of the thermistor, as well as the subsequent sending of the data to the PC via USB communication.
- A PC responsible for controlling and configuring the microcontroller for the designed tests, as well as for storing the data obtained from the measurements. Programming of the microcontroller is carried out by the Arduino IDE application, an environment designed for such purposes.

To prepare the solutions of salts, they were first dried at 100°C + –0.1°C. An analytic balance was used with a resolution of 0.0001 g to weigh the salts, which were then diluted to obtain solutions with different concentrations (Table 1).

The composition of solution 1 was calculated in a study of seawater in which the typical concentrations of these salts in seawater were determined [6].

The solutions were stored in labelled amber bottles to preserve them from the effect of light. The main salts present in sea water were used. The $NaCl/MgCl_2/KCl$ solutions were prepared at different concentrations. According to studies carried out [8], molar conductivity (S $cm^2$/mol) at 25°C depends on the type of salt: $K^+$ 73.5; $Na^+$ 50.1; $H^+$ 349.8; $Cl^-$ 76.3; $OH^-$ 198.0; $HCO_3^-$ 45.4.

The relationship between EC, T and molar concentration is reflected in Eq. (1) with the adjustment coefficients a and b.

The data obtained for specific concentrations are shown for the three types of salts according to the method of the

Table 1
Concentrations of experimental solutions

| Solution number | Salt type | [Cl] g/L | [Sal] g/L |
|---|---|---|---|
| Solution 1 | NaCl | 10.7838 | 17.7706 |
| | $MgCl_2$ | 1.2837 | 3.4462 |
| | KCl | 0.3991 | 0.8386 |
| Solution 2 | $NaCl/MgCl_2/KCl$ | – | 5 |
| Solution 3 | $NaCl/MgCl_2/KCl$ | – | 10 |
| Solution 4 | $NaCl/MgCl_2/KCl$ | – | 15 |
| Solution 5 | $NaCl/MgCl_2/KCl$ | – | 20 |

final test in which the solution is being cooled while monitoring the value of conductivity and temperature. As can be observed, conductivity with temperature has a linear relationship, of the type:

$$EC = a \cdot T + b \quad (1)$$

The adjustment coefficients, *a* and *b*, of the linear relationship between EC and T are constant for the different salts used and depend on the molar concentration, as discussed later in the results section. Therefore, with high temperature the value of EC is higher than with low temperature, also depending of the molar concentration and the values of the coefficients "*a*" and "*b*" of Eq. (1).

The experiments were carried out at 5 different temperatures, for the KCl solution at 8°C, 12°C, 19°C, 26°C and 30°C and for the NaCl solution at 3°C, 12°C, 18°C, 28°C and 30°C.

The 5 prepared solutions were heated to approximately 60°C. Once the temperature had been reached, the conductivity electrode and thermistor were inserted and data began to be acquired for each of the prepared solutions down to a temperature of 10°C. The temperature was lowered using ice in a water bath in order to take the EC measurements at the five levels specified from 60°C to 10°C.

Fig. 2 shows the relationship between the signal range of 0 to 1,023, corresponding to 10 bits of capacity, and T for the thermistor used. The values shown in Fig. 2 are from 0°C to 100°C, but finally we used only the range between 10°C and 60°C as this is considered the more frequent interval and sufficient for the results required in this study.

## 3. Results and discussion

This section shows the results obtained based on the experimental design proposal. Three types of salts with different concentrations were used, as follows: sodium chloride, potassium chloride and magnesium chloride. The numerical tool of the open-source code SCILAB was used for data treatment.

### 3.1. Laboratory tests

Firstly, the data obtained for certain concentrations are shown for the three salt types following the established test

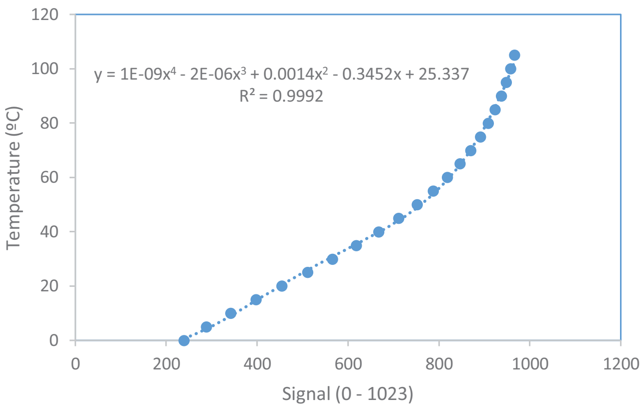


Fig. 2. Temperature curve for the thermistor used.

method in which the solution is cooled while monitoring EC and T values. As can be seen in Fig. 3 and Table 2, EC has a linear relationship with T which follows Eq. (1).

Figs. 4 and 5 show EC vs. T for two different solution concentrations of sodium chloride and potassium chloride, respectively.

### 3.2. Results obtained with numerical tools

Secondly, the SCILAB open-source numerical tool was used to process the data and develop, by way of example, Figs. 6 and 7 which show EC increasing with the concentration of sodium chloride and potassium chloride, respectively. As can be seen, in Figs. 6 and 7 there are five temperature lines, each representing an average temperature to which the solution was submitted. For all working temperatures there is a good linear fit of the data ($R^2 > 0.9$) in all cases. It should be noted that in the case of the temperature of 30°C it was not possible to take a reading at the concentration of 20 g/L as it exceeded the working range. In the case of 28°C, the reading of slightly above 40,000 uS was accepted despite being above the calibrated range because of its linear fit.

Fig. 7 shows similar behavior to that obtained with sodium chloride. Since the conductivity of potassium chloride is lower compared to that of sodium chloride at the same salt concentration, the conductivity sensor gave readings for all concentrations of KCl. A good linear fit of the concentration-conductivity relationship can be observed for temperatures from 8°C to 30°C.

As reported in different studies [7–9], molar conductivity is a function of the concentration of a salt (Table 3).

Eq. (2) shows the relationship between EC and molar concentration.

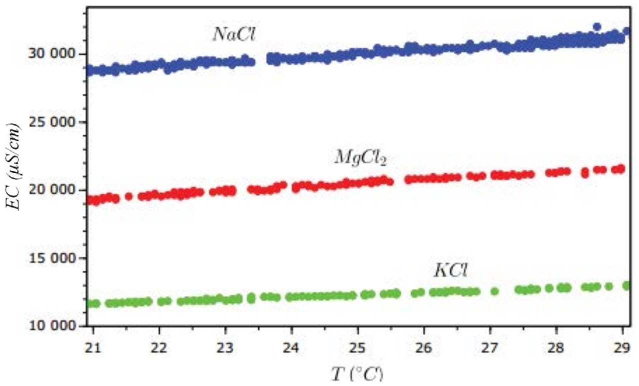


Fig. 3. Electrical conductivity vs. temperature comparing three different salts.

Table 2
Values (*a*) and (*b*) for the different salts

| Salt | *a* | *b* |
|---|---|---|
| NaCl | 382.19 | 20,941.45 |
| $MgCl_2$ | 366.34 | 16,791.42 |
| KCl | 153.12 | 8,460.17 |

$$EC_{25} = \left(\text{Ion 1 Molar Cond.} + \text{Ion 2 Molar Cond.}\right) \times 10^6 \times \frac{1}{1{,}000} \times \left[\text{M}\right]\text{Solution} \quad (2)$$

### 3.3. Comparison of final results

Finally, a comparison of the theoretical (calculated) values and the actual (measured) values obtained can be carried out to determine the error (Table 4). This is only feasible for solutions at temperatures close to 25°C, as the model is valid for that temperature.

As can be seen in Table 4, for both types of solution the biggest difference between measured and calculated conductivities using the system proposed was for concentrations of 5 g/L, obtaining an error of over 60%. This is because the conductivity probe is calibrated from 10,500 uS/cm, and so the unreliability of results for concentrations below this value is to be expected. They are shown nevertheless as they maintain a linear relationship with T.

Importantly, for concentrations of 10–20 g/L the errors determined did not exceed 15%.

From this, it can be concluded that the data acquisition system (whose components and operation were previously described) give better results for the measurement of electrical conductivity in concentrations higher than 5 g/L.

It can be seen in Fig. 8 that there is a linear relationship between EC and T for the sodium chloride solution, the potassium chloride solution and for the salt mix simulating seawater.

However, the slopes of these lines vary depending on the salt. This shows that the sample should be brought to a temperature of 20°C to carry out the measurement. According to Millero et al. [6], a 1°C increase means a 2% increase in conductivity.

An investigation carried out at the Universidad de Las Palmas de Gran Canaria (Canary Islands, Spain) [10] showed the slopes obtained and the intercepts that relate these variables in a temperature range of 21°C to 29°C. The data disagree with the slopes and intercepts determined in the present study, which can be attributed to the range in which we performed the regression (from 3°C to 40°C).

Table 5 shows the experimental and theoretical $EC_{25}$ result, at 40°C for different salts (salt mix, NaCl and KCl), to

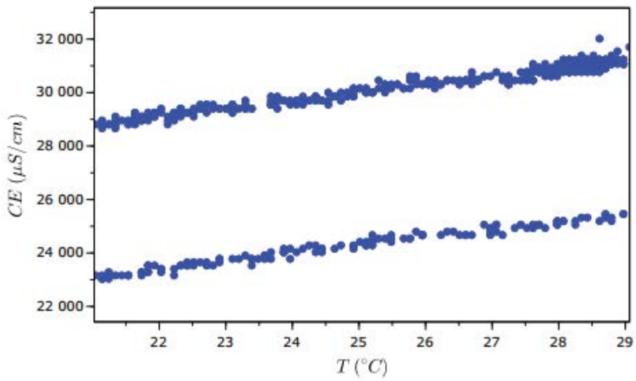


Fig. 4. Electrical conductivity vs. temperature comparing two solutions of NaCl.

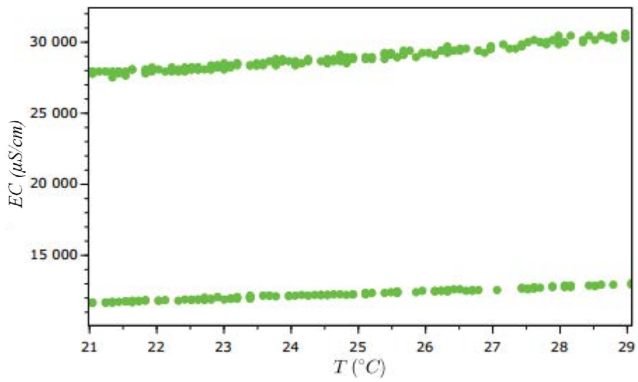


Fig. 5. Electrical conductivity vs. temperature comparing two solutions of KCl.

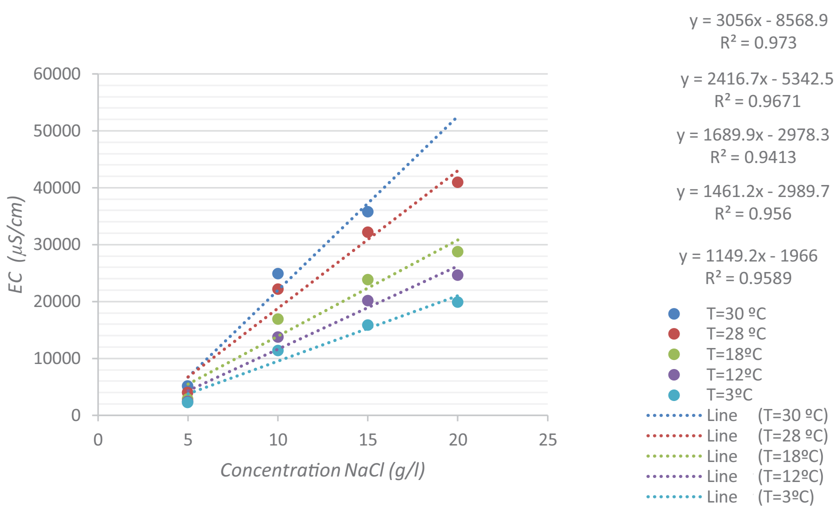


Fig. 6. Electrical conductivity vs. different salinity concentrations of NaCl at different temperatures.

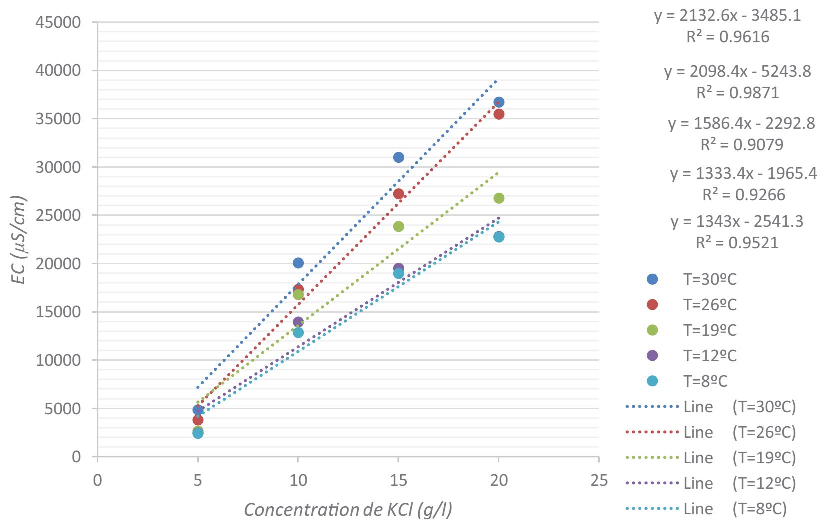


Fig. 7. Electrical conductivity vs. different salinity concentrations of KCl at different temperatures.

Table 3
Molar conductivities of common ions in salts

| Ion | Molar conductivity (S cm$^2$/mol) at 25°C |
|---|---|
| $K^+$ | 73.5 |
| $Na^+$ | 50.1 |
| $H^+$ | 349.8 |
| $Cl^-$ | 76.3 |
| $OH^-$ | 198.0 |
| $HCO_3^-$ | 45.4 |

calculate the percentage error between them. The theoretical $EC_{25}$ results were obtained through Eq. (3).

$$*EC_{25} = EC_T\left[1+0.022\left(25-T\right)\right] \quad (3)$$

Fig. 9 shows the relationship between TDS and EC. The most commonly used formula to perform the theoretical calculation of TDS from conductivity at 25°C is the following [3,11,12]:

$$TDS = 0.7 \times \text{Conductivity}\left(\frac{uS}{cm}\right) \quad (4)$$

In this work, using the data of the measurements made in a temperature range of 24°C to 29°C, we had an intercept of 0.1348 and a slope of 0.54. The difference in slope obtained can be attributed to this. However, it has been reported elsewhere that this factor can vary between 0.5 and 0.9 according to the type of water.

Fig. 10 shows the relationship between resistance and temperature (a) and between temperature and voltage (b), compared with the data provided by the manufacturer.

Figs. 11 and 12 show the experimental results of EC vs. T at different KCl and NaCl solution concentrations, respectively, and the theoretical values calculated based on the ISO 7888-1985 model.

EC is a measure of the current conducted by ions present in the water (phenomenon of conductors of the second kind) and depends on the concentration and nature of the ions, and the temperature and viscosity of the solution [13].

It is considered that the results satisfy the expectations of the authors. The results obtained with the

Table 4
Calculated and measured values of electrical conductivity at 25°C at different molarities

| Solution concentration (g/L) | Molarity | Calculated | Measured | Error |
|---|---|---|---|---|
| NaCl | | Electrical conductivity (µS/cm) | | |
| 5 | 0.08554 | 10,812.66 | 4,027.00 | 62.76% |
| 10 | 0.17108 | 21,625.32 | 22,234.00 | 2.83% |
| 15 | 0.25662 | 32,437.98 | 32,230.00 | 0.64% |
| 20 | 0.34217 | 43,250.64 | 40,973.00 | 5.6% |
| KCl | | Electrical conductivity (µS/cm) | | |
| 5 | 0.06715 | 10,060.44 | 3,827.18 | 61.96% |
| 10 | 0.13431 | 20,120.88 | 17,363.00 | 13.71% |
| 15 | 0.20147 | 30,181.32 | 27,251.00 | 9.71% |
| 20 | 0.26863 | 40,241.77 | 35,505.00 | 11.77% |

Table 5
Comparison of theoretical and experimental $EC_{25}$ results at 40°C for different salts

| Salt | Temperature | Conductivity at 40°C (uS/cm) | $EC_{25}$ (uS/cm)[a] | | % Error |
|---|---|---|---|---|---|
| | | | Theoretical | Experimental | |
| Salt mix | | 54,243 | 36,342.81 | 38,661.0 | 6.38% |
| NaCl | 40°C | 38,658.8 | 25,901.37 | 29,147.0 | 12.53% |
| KCl | | 32,045.2 | 21,470.284 | 25,681.0 | 20.45% |

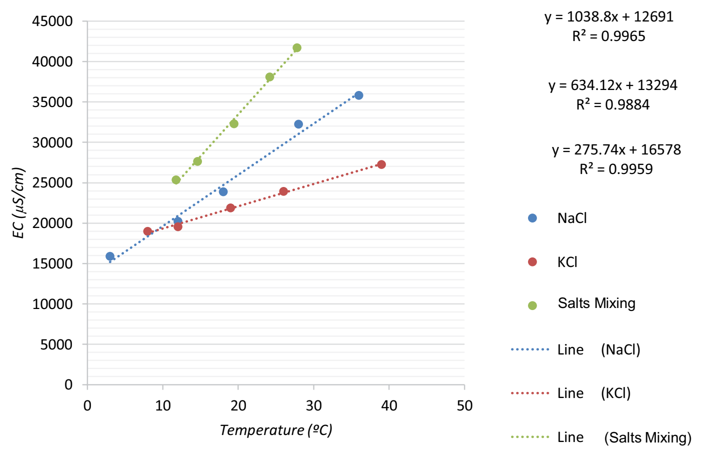


Fig. 8. Effect of temperature on conductivity [NaCl] = 15 g/L; [KCl] = 15 g/L.

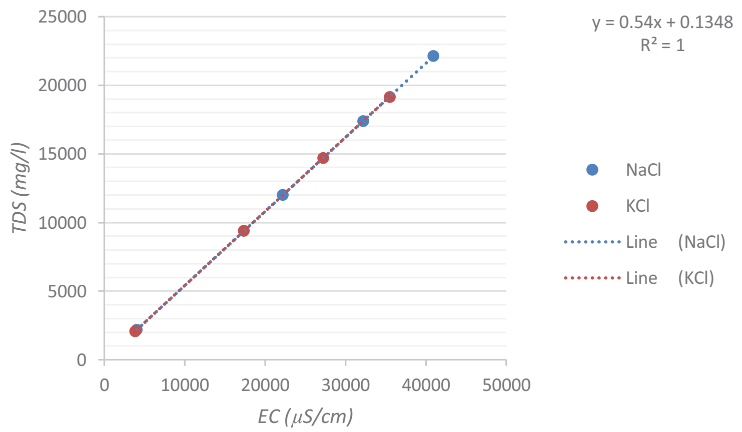


Fig. 9. Total dissolved salts (TDS) content vs. electrical conductivity.

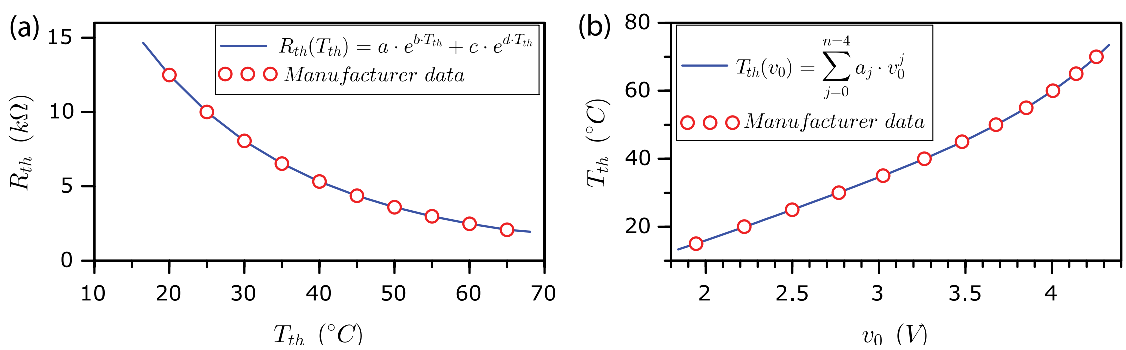


Fig. 10. Relationship between resistance and temperature (a) and between temperature and voltage (b) and resistance, compared with the data provided by the manufacturer.

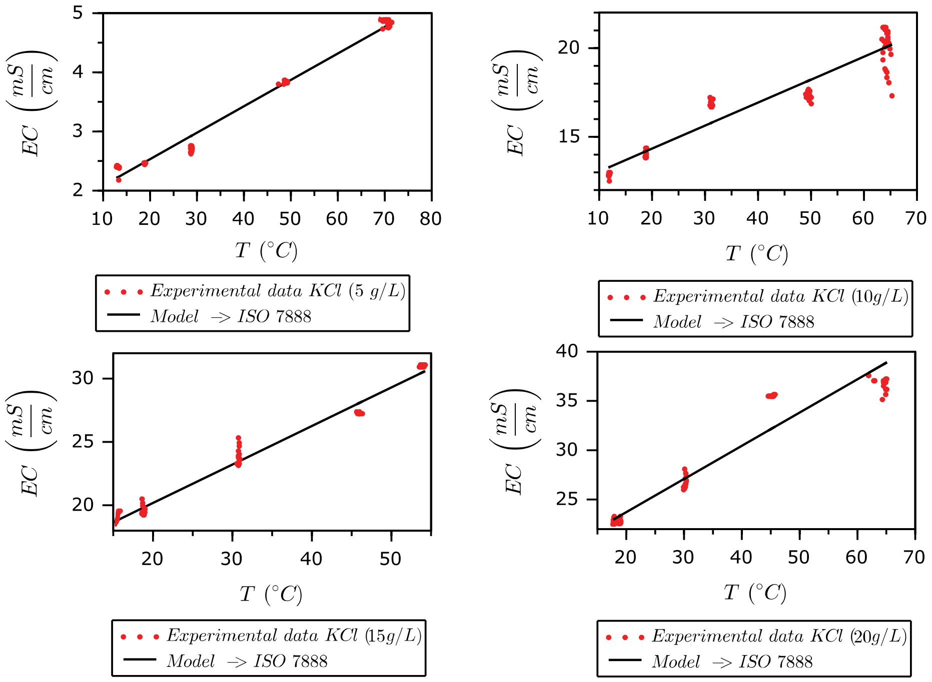


Fig. 11. Experimental results of EC vs. T at different KCl solution concentrations and theoretical values calculated based on the ISO 7888-1985 model.

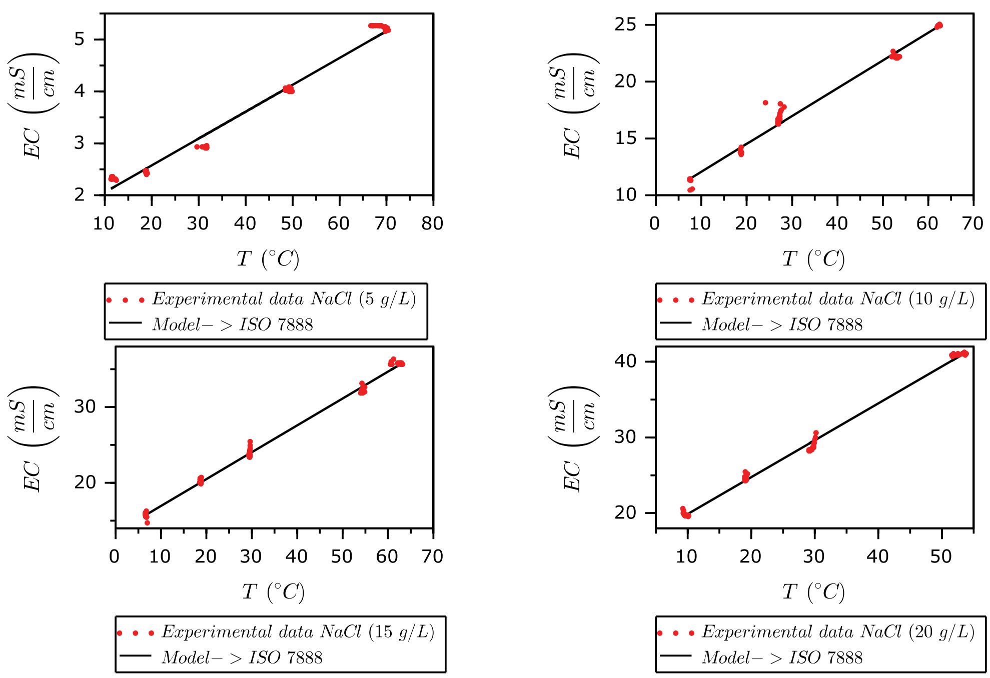


Fig. 12. Experimental results of EC vs. T at different NaCl solution concentrations and theoretical values calculated based on the ISO 7888-1985 model.

designed system followed appropriate methods to observe the variability of the EC of different salt solutions with T. The results demonstrate that this experimental design can be used to achieve the objective of helping students to obtain and deepen their understanding of the relationship between EC and T, which is in the form of a linear fit following Eq. (3). By way of example, Fig. 12 shows the experimental results of the relationship between EC and T for different NaCl solution concentrations and compares them with the ISO 7888-1985 model [13], demonstrating the accuracy of the experimental design system. The relationship between

EC and TDS presented in Eq. (4) has also been shown. The results obtained also support the theoretical formula used to calculate TDS from conductivity at 25°C [3,11,12].

## 4. Conclusions

A low-cost experimental design using an embedded Arduino Nano microcontroller system has shown its utility to allow students to observe and deepen their understanding of the phenomena and relationships between the temperature and electrical conductivity of brackish water.

In addition to the low cost of the different devices used in the proposed experimental design, the flexibility of the system, both in terms of the physical devices and computer applications used, facilitates its modification by students for use in other operations. This flexibility in the design characteristics is enhanced using open-source computer applications, as well as easily modifiable devices.

A series of tests were performed to test the technical and pedagogical feasibility of the proposal. From the experimental results obtained, the feasibility of the proposed learning proposal is verified.

The results show that the data acquisition system is a useful tool when making measurements and correlating different parameters in real time. It was possible to corroborate the validity of the linear relationship between electrical conductivity and temperature and to verify that the relationship between total dissolved solids and conductivity is not constant but varies according to the type of salt (with additional research also showing that it varies according to the composition of the water). Finally, the relationship between solution concentration and total dissolved solids was found to be valid for any concentration range if the sensor is within its quantification range (in the tests we worked with a concentration of 5 g/L that was below the calibration limit).

It is recommended to conduct further studies on the effect of the type of salt on the concentration of dissolved solids to establish reliable general formulas to associate one variable with the other.

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