

# Physical Analysis of a Waterproof Temperature Sensor Responsiveness for Agricultural Applications

João E. M. Perea Martins<sup>1</sup>

## INFO

Received 11.01.2022

Accepted 15.08.2022

Available on-line 23.01.2023

Responsible Editor: László

Várallyai

## Keywords:

Sensor, Temperature,  
responsiveness, Irrigation,  
Aquaculture.

## ABSTRACT

The water temperature is highly relevant in agriculture and aquaculture, and it motivated the present work that analyzes the responsiveness, accuracy and precision of a digital low-cost waterproof temperature sensor model DS18B20, which requires only a simple hardware to allow its connection to microcontrollers and presented a satisfactory performance in this work analysis. Despite the focus on a specific sensor, this work presents nonexclusive analysis techniques that can allow the analysis of other temperature sensors. The water temperature relevance justifies the present work, whose results are presented with quantitative parameters and justified according to concrete measurement theories.

## 1. Introduction

Water temperature is an important parameter with influence on several physical-chemical and biological processes, such as chemical reactions rate, dissolved oxygen concentration, conductivity, ecosystems and life conditions (Jafar 2020; Omer 2019; Kale 2016).

Besides the air temperature, the water temperature can also influence the plants' metabolism that becomes slower under cool conditions with consequences on their growth rate and consequently on the agricultural production. In addition, the cold-water temperature can also harm microorganisms that may be beneficial for the plant's health, and on the contrary, a controlled hot water temperature can be useful to eliminate undesirable bacteria of some seed types (Canning 2019; Loperfido 2014; Nxawe 2010). Another relevance of water temperature relates to irrigation where it can influence the plant behavior and the irrigation process itself, which may bring special attention to aspects associated with drip irrigation as the water usage efficiency, fertilization requirements, soil water infiltration and emitter performance (Peng 2021; Seyedzadeh 2020; Liu 2019; Jamrey 2018). Besides the influence on terrestrial animal nutrition, the water temperature is also a very important factor for fish farming, where it can influence the fishes' physiological parameters such as metabolism, growth, and reproduction (Islam, 2020), therefore it has a great impact on aquatic systems, and it is a key factor for aquaculture farmers' planning and decisions (Besson 2016; León 2006).

The present contextualization shows that the water temperature is a physical parameter that influences agriculture directly with scientific, social and economic effects, which justifies the efforts to analyze and improve the processes, focused on the water temperature measurement. Based on this fact, this article shows a process to verify how fast is the waterproof sensor DS18B20 and how to verify its accuracy and precision. In relation to social aspects, it may be interesting to highlight examples associated with human health and jobs. Global ocean surface temperature has increased by approximately 0.13°C every 10 years in the past 100 years (Xu 2021) and it affect the fish's metabolism, which caused the migration of several species to survive and reproduce (Xu 2021; Kuczynski 2017).

<sup>1</sup> João E. M. Perea Martins  
São Paulo State University (UNESP)  
joao.perea@unesp.br

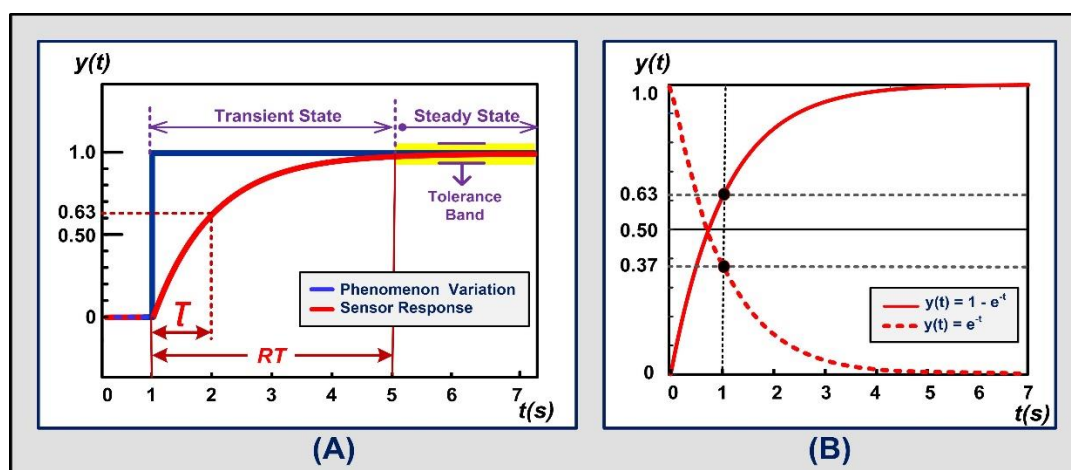
This phenomenon can influence human health and development because globally fish provided more than 3.3 billion people with 20 percent of their average per capita intake of animal proteins, but it can reach 60 % in countries such as Gambia, Sierra Leone and Ghana, where fishing is frequently an subsistence activity (FAO 2020; Béné 2015). Besides, even in regions with large fishing companies, fish migration can affect negatively these companies' structure and the offer of jobs, which serious social impacts.

As important as the analysis of the DS18B20 sensor itself, are the presented experimental methods that can be used for other temperature sensors analysis. These methods include hardware, software, and statistical aspects, and are detailed in the sections:

- The section 4 explains the sensor time constant measurement with two Styrofoam cups and an electronic system, whose hardware and software aspects are detailed.
- The section 5 explains explain the sensor accuracy and precision verification based on the statistical analysis of a pre-composed data set.

## 2. The Time Constant Concept

There are temperature sensors faster than others and depending on the application, some additional seconds can make an important difference. An ideal sensor should detect the variation of a phenomenon, such as temperature or humidity at the same moment of its occurrence, but in practice, sensors have a *response time* (*RT*) that is an undesired delay in the detection of the phenomenon intensity variation when it occurs abruptly as a step-function. Figure 1(A) shows this sensor response (red line) that technically is defined as a parameter called *time constant* ( $\tau$ ), which is a particular case of the response time. It represents the time required by the sensor to reach 63.2% of the measured phenomenon value when it changes abruptly (blue line). The response time has a less rigorous definition. It represents the time required by the sensor to reach a value close to the measured phenomenon value, which usually is defined at least 90% of this value. Figure 1(B) emphasizes the sensor response variation can be either ascending or descending, but both presents the same time constant concepts.



**Figure 1.** (A) The time constant ( $\tau$ ) and (B) the natural bounded exponential curves.

The ascending and descending figure 1(B) curves are respectively expressed as:

$$(1) \quad y(t) = a + (b - a) (1 - e^{-kt})$$

$$(2) \quad y(t) = a + (b - a) e^{-kt}$$

Where  $y$  represents the physical phenomenon variation over time,  $t$  is the time instant,  $a$  is the lower limit (smallest  $y$  value),  $b$  is the upper limit (highest  $y$  value), and  $k$  is the phenomenon variation rate.

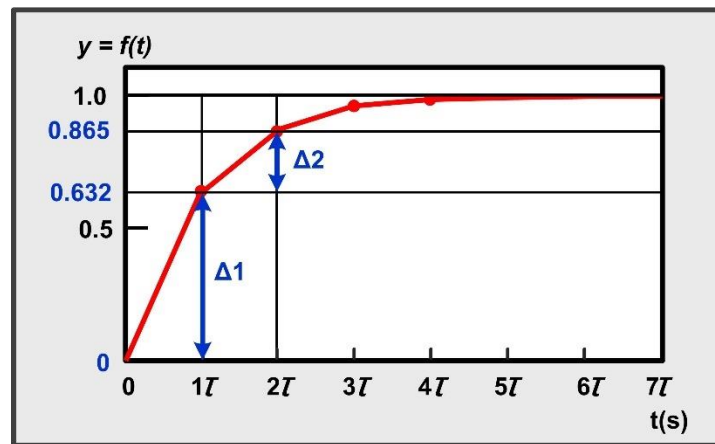
In fact, the figure 1(B) curves represent a particular case of bounded exponential equations where the variation is relativized in a range from 0 to 1, with  $k$  equals 1, and therefore, in this case, the equations 1 and 2 are respectively simplified as:

$$(3) \quad y(t) = 1 - e^{-t}$$

$$(4) \quad y(t) = e^{-t}$$

In this case, when  $t$  equals 1, the curve values are computed as  $(1 - e^{-1})$  that equals 0.632, which justifies the *Time Constant* ( $\tau$ ) value fixed at 63.2%. Based on the same principle, the first time for the natural exponential decaying is computed as  $(e^{-1})$  that equals 0.368.

Note that, figure 2 shows the exponential growth function varies proportionally for successive discrete values of the time constant ( $1\tau$ ,  $2\tau$ ,  $3\tau$ , ...,  $n\tau$ ), and the function variation ratio between two successive periods constant is a factor  $e$  (2.718).



**Figure 2.** The bounded exponential growth for discrete-time values

The analysis of  $\Delta 1$  and  $\Delta 2$  variations in figure 2 shows that the ratio between two successive discrete variations separated by a period equal to  $\tau$  is expressed as:

$$(5) \quad \frac{\Delta_n}{\Delta_{n+1}} = \frac{y_n - y_{(n-1)}}{y_{(n+1)} - y_n} = 2.718$$

For example, the ration  $\Delta 1/\Delta 2$  in figure 2 is  $(0.63-0)/(0.865-0.632)$  that equals 2.718, and it demonstrates that the equation 5 can also be expressed as:

$$(6) \quad \Delta_{n+1} = \frac{\Delta_n}{2.718} = \Delta_n \frac{1}{2.718} = \Delta_n 0.368$$

### 3. A Referential for the Temperature Variation Rates

Temperature sensors have time constant values in a usual range from fractions to up a few hundred of seconds, but for practical approaches, the ideal time constant magnitude will depend on the requirements of each application. For example, if an experiment requires the temperature measurement every 15 minutes in a lake, then even sensors with time constants in the order of a few hundred of seconds will be satisfactory because the natural water heating is slow. Remember that water has a large specific heat, fixed at  $4.186 \text{ J/(g} \cdot ^\circ\text{C)}$ , and therefore it requires a large amount of heat to increase its temperature, which justifies the moderate lake water temperature even on hot summer days. Differently, some other systems such as conventional PCR (Polymerase chain reaction) experiments (Miralles 2013)

or pasteurization processes (Castillejo 2018) usually can operate with temperature variation rates in order of some units of degree Celsius per second, therefore in these cases, sensors with small-time constants become desired.

A quantitative example of a relative fast cooling is the natural water-cooling process, which is expressed by the Newton's law of cooling as:

$$(7) \quad T(t) = T_a + (T_h - T_a) e^{-kt}$$

Where  $T(t)$  is the water temperature at time  $t$ ,  $T_a$  is the ambient temperature,  $T_h$  is the hot water temperature at initial time, and  $k$  is the cooling rate defined experimentally.

If the values of  $T_a$ ,  $T_h$  and at least one experimental value  $T(t)$  are known, then the  $k$  value can be computed also according to equation 7, and next the same equation can compute all the theoretical temperature values over time. Supposing a process where  $T_a$  was 25 °C,  $T_h$  was 75 °C, and a  $k$  value was computed at 0.005. In this case, the temperature falls from 75.0 °C to 69.0 °C in the first 30 seconds, then the sensor time constant selection must consider this rate. Remember that general cooling processes are important for several agricultural applications (Liu 2021, Plasquy 2021) so this work shows as an additional associated with the figure 3 experiment, which was designed for the sensor time constant verification, but can also measure the real cooling curve of a liquid. The user must only put the sensor inside a hot liquid and the temperature drop will be shown every second during the colling process.

#### 4. The Sensor Time Constant Measurement

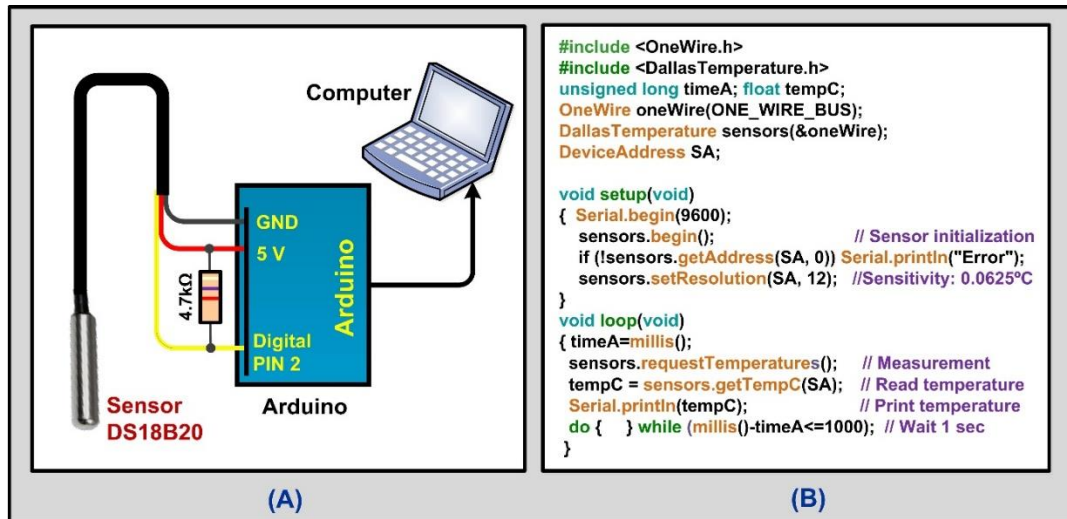
Several parameters influence the sensor time constant, such as the sensor features itself (mass, surface area, volume, and encapsulation potting material), the external enclosure box, the immersion medium (liquid, gas, or solid), and the immersion fluid agitation. All these parameters compose a dynamic scenario and therefore the users must know that the sensor time constant may present variations according to different influences.

This work verified the DS18B20 waterproof sensor response time in water through a simple but efficient process that follows the steps:

1. Fill a Styrofoam cup, called "A", with hot water
2. Fill a Styrofoam cup, called "B", with water at room temperature
3. Immerse the sensor in the water in cup A (colder) and wait for its stabilization, which occurs when the sensor value reaches the true water temperature value or oscillates repeatedly around it. The stabilization is fundamental to allow a reliable experiment.
4. Remove the sensor from the cup A and then insert it immediately in the cup B (hotter), and wait for its stabilization
5. Remove the sensor from the cup B and insert it immediately again in the cup A, and wait for its stabilization

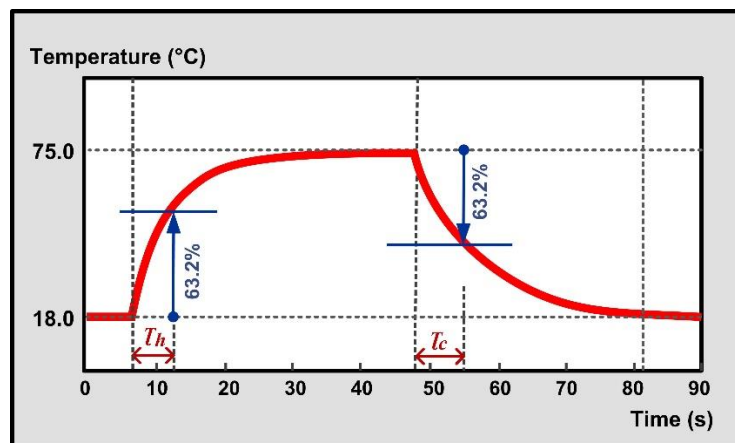
This experiment used a covered Styrofoam coffee cup with a small hole in the lid to allow the sensor insertion. Styrofoam is interesting for this type of experiment because it presents a good thermal isolation between the water and the surroundings, which occurs because it has small internal air bubbles that prevent the heat flow through it, and also have a small mass.

Figure 3(A) shows the experiment hardware design, which is based on the waterproof DS1820 sensor connected to an Arduino board through a 4.7 K $\Omega$  resistor, and figure 3(B) shows the program that must run on the Arduino board. This program measures the water temperature always at one-second intervals and sends the value to a computer that runs the Arduino IDE to show the received data. This program also defines the sensor sensitivity at 0.0625 °C, which becomes the smallest temperature change that it can detect.



**Figure 3.** (A) The hardware and (B) the software of the proposed system.

This work performed the experiment above. Figure 4 shows a heating and a cooling curve of the measured temperature values, where the time constant for the heating process ( $\tau_h$ ) was 6.2 seconds and for the cooling process ( $\tau_c$ ) was 6.9 seconds.



**Figure 4.** The temperature variation and the time constant ( $\tau$ ) values.

This experiment, like any other experiment involving physical measurements, may be susceptible to errors and therefore the experiment repetition is important to allow a more reliable analysis through a statistical interpretation. The experiment was repeated ten times under the same conditions and Table 1 shows the descriptive statistics of these time constant measurements.

**Table 1.** The statistical time constant ( $\tau$ ) analysis.

Parameter	Growing Variation	Decreasing Variation
Mean	6.20 s	6.90 s
Standard deviation	0.41 s	0.47 s
Coefficient of variation	6.4%	6.8%
Maximum value	7.0 s	7.5 s

For a realistic comparison, a mercury-in-glass thermometer presents a larger time at about 10 seconds (Zananetti 1988; Thomsen 1998). Thermistor, which is a type of resistive temperature sensor,



can present time repose in the range of a fraction of seconds (Goshlya 2018), but popular and inexpensive thermistors usually operate within a range from units to dozens of seconds. Thermocouples are sensors that consist of two different types of metals joined at one end, which produce naturally a voltage proportional to the temperature and can present models with time response in the range of milliseconds (Puzdrowska, 2016; Sarnes, 2007). Note that, like the DS18B20, thermistors and thermocouples also require a Stainless-steel sheath to allow their operation as waterproof devices, and this sheath usually may increase the assembled sensor time constant.

Although the DS18B20 time constant is greater concerning thermistors and thermocouples, this sensor presents advantages such as better precision, resolution, stability, and electronic interfacing facility. Besides, this sensor time constant at units of seconds can be extremely satisfactory for common agricultural application, and therefore all these facts justify the usage of this sensor. The present work focuses on the waterproof DS18B20, but this sensor has another version without the stainless-steel sheath that is used for the air temperature measurement, where the time constant increases significantly. However, even so, this sensor has been widely used satisfactorily in several works that need air temperature measurement (Jankovec 2013; Belmili 2010).

## 5. The Sensor Accuracy and Precision

When the sensor response reaches the true phenomenon value, it should keep constant in time with this value. However, usually it doesn't occur perfectly because real sensors response may present oscillations around the phenomenon value and in some cases, this oscillation can occur even around values slightly higher or smaller than the true phenomenon value. It justifies the definition of a variation or error range called *tolerance band*, where the sensor response is theoretically confined. Besides, as explained, the sensor response can vary around a value slightly different value than the phenomenon value, which also justifies the time constant fixation at 63.2% of the true measured value because it is a threshold expected to be reached by any sensor under normal operational conditions.

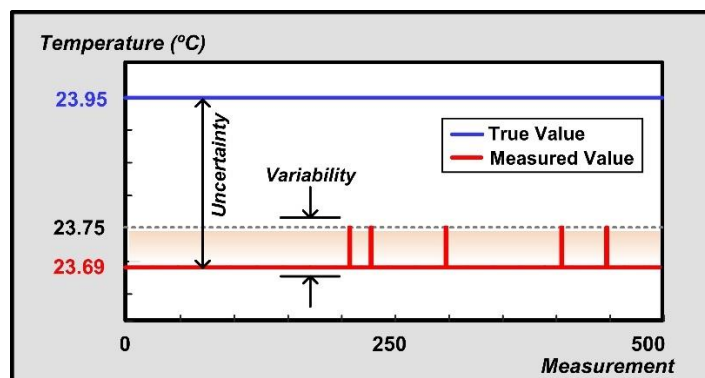
Theoretically, a sensor reaches 99.3% of the measured phenomenon value at  $5\tau$ , and this time becomes a referential where the sensor response starts a new stage called steady stage, whose physical limits range are defined by the tolerance band.

The sensors behavior in the steady-state can be more technically analyzed according to two physical sensor parameters called *accuracy* and *precision*, which are different but sometimes are misused as synonyms. The International Vocabulary of Metrology (VIM) (JGCM, 2012) defines the *measurement accuracy* as "closeness of agreement between a measured quantity value and a true quantity value of a measurand", and the *measurement precision* as "closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions". In other words, accuracy represents the maximum expected difference between the true value and the sensor response, while precision represents the repeatability of the sensor response for the same measurement.

Curiously, both concepts are only qualitative (Martins, 2019; JGCM 2012; De Bièvre 2012; Wallard 2012) and the accuracy is quantitatively associated with a parameter called *uncertainty* that is defined as  $T \pm \theta$ , where  $T$  is true phenomenon value and  $\theta$  is a maximum difference between the sensor response and the true phenomenon value, while the precision is a variability numerically associated with the *Standard Deviation* or the *coefficient of variation* of several measurements under the same conditions.

To verify the waterproof sensor DS18B20 behavior in the steady-state, this work investigated its precision and accuracy through an experiment that analyzed mathematically the result of several measurements under the same conditions. Firstly, the experiment immersed the sensor in the water and waited for 60 seconds that is a period longer than the minimum theoretical period of 35 seconds ( $5\tau$ ) required for this sensor operation in the steady state. The still water (150ml) was inside a Styrofoam cup and its temperature was measured at 23.95 °C with a calibrated temperature thermometer. Next, the

experiment performed 500 temperature measurements at intervals of one second each and figure 5 shows the measurement values over time.



**Figure 5.** Measurement values of the water temperature.

Table 2 shows the statistical analysis of the figure 5 data, which presented 495 measurement values at 23.69 °C and five at 23.76 °C. It represents a little variability that is quantified by the small coefficient of variation and indicates an excellent sensor precision. The uncertainty was at 0.26°C, which is small and indicates a good sensor accuracy. The accuracy and precision can vary slightly according to each sensor piece, but they must keep in the same order of magnitude.

**Table 1.** The statistical time constant ( $\tau$ ) analysis.

Parameter	Value (°C)
Mean	23.6906
Standard deviation	0.006
Coefficient of variation	0.025%
Maximum value	23.76
Minimum value	23.69

This sensor presented a very good level of accuracy and precision, and it is interesting to emphasize that, sensors with good precision allows a later mathematical data correction with a simple addition, which isn't possible for sensors with poor precision (Martins 2019). For example, if all the measured values in the figure 5 (red line) were added by 0.26 (uncertainty value), then almost of them would have the same value of the true measured phenomenon (blue line).

## 6. Conclusions

This work proved that is possible to verify the time response of a waterproof sensor in water with a simple method and it also showed that the low cost DS18B20 waterproof sensor presented a satisfactory time constant at about 7.2 seconds, which is better than traditional mercury-in-glass thermometer. It ensured very a good level of accuracy and precision that tend to be better than traditional analogue sensors as thermistors and thermocouples.

## References

- Belmili, H et al. 2010 'Design and development of a data acquisition system for photovoltaic modules characterization'. *Renewable Energy*, v. 35, p. 1484-1492. DOI: 10.1016/j.renene.2010.01.007
- Besson, M et al. 2016 'Influence of water temperature on the economic value of growth rate in fish farming: the case of sea bass (*Dicentrarchus labrax*) cage farming in the Mediterranean'. *Aquaculture*, v. 462, pp. 47-55. DOI: 10.1016/j.aquaculture.2016.04.030.

- Béné, C. et al. 2015 'Feeding 9 billion by 2050 – Putting fish back on the menu'. *Food Security*. Vol. 7, pp. 261–274, DOI: 10.1007/s12571-015-0427-z
- Canning, AD, Russell GD 2019 'Ecosystem health indicators—Freshwater environments' in *Encyclopedia of Ecology*, Fath B editor, Elsevier, v. 1, pp. 46-60, ISBN 978-0-444-63768-0
- Castillejo, N *et al.* 2018 'Microwave heating modelling of a green smoothie: Effects on glucoraphanin, sulforaphane and S-methyl cysteine sulfoxide changes during storage'. *Journal of the Science of Food and Agriculture*, v. 98, n. 5, pp. 1863-1872. DOI: 10.1002/jsfa.8665
- De Bièvre P. 2012 'The 2012 International Vocabulary of Metrology: VIM'. *Accreditation and Quality Assurance* v. 17, n.2, pp. 231-232. DOI: 10.1007/s00769-012-0885-3
- FAO (Food and Agriculture Organization of the United Nations) 2020 'The State of World Fisheries and Aquaculture'. Rome, ISSN 2410-5902, DOI: 10.4060/ca9229en
- Goshlya, R. Yu et al. 2018 'The use of thermistors for the measurement of rapidly changing temperatures'. *AIP Conference Proceedings*. AIP Publishing, v. 2007, p. 030018. DOI: /10.1063/1.5051879
- Islam, MD et al. 2020 'Extreme ambient temperature effects in European seabass, *Dicentrarchus labrax*: Growth performance and hemato-biochemical parameters'. *Aquaculture*, v. 522, pp. 735093,. DOI: 10.1016/j.aquaculture.2020.735093
- Jaffar, A et al. 2020 'The Influence of Physico-Chemical Parameters to Determine Water Quality: A Review'. *Journal of Electrical and Electronic Systems Research*, v.17, DOI: /10.24191/jeesr.v17i1.016
- Jamrey, PK, Nigam, GK 2018 'Performance evaluation of drip irrigation systems'. *The Pharma Innovation Journal*, v. 7, n. 1, pp. 346-348.
- Jankovec, M; Topic M 2013 'Intercomparison of temperature sensors for outdoor monitoring of photovoltaic modules'. *Journal of Solar Energy Engineering*, v. 135, n. 3, p. 031012. DOI: 10.1115/1.4023518
- JGCM (Joint Committee for Guides in Metrology) 2012 'International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)'. *International Bureau of Weights and Measures (BIPM) Ed.*, Sevres - France.
- Kale, VS 2016 'Consequence of temperature, pH, turbidity and dissolved oxygen water quality parameters'. *International Advanced Research Journal in Science, Engineering and Technology*, v. 3, n. 8, p. 186-190. DOI: 10.17148/IARJSET.2016.3834
- Katheline Hua et al. 2019 'The Future of Aquatic Protein: Implications for Protein Sources in Aquaculture Diets'. *One Earth*, Vol. 1, no. 3, pp. 316-329, DOI: 10.1016/j.oneear.2019.10.018.
- Kuczynski, L. et al. 2017 'Indirect effect of temperature on fish population abundances through phenological changes' *PloS one*, Vol 12, no 4, DOI: 0.1371/journal.pone.0175735
- León, CJ et al 2006 'The effects of water temperature in aquaculture management'. *Applied Economics*, v. 38, n. 18, pp. 2159-2168. DOI: 10.1080/00036840500427379
- Liu, Fang et al. 2021 'Thermodynamics analysis for forced air pre-cooling of cherry', *Journal of Food Process Engineering*, Vol. 44, no. 11, pp. 1-11, DOI:10.1111/jfpe.13881
- Liu, L H et al. 2019 'Effects of water temperature on soil water infiltration characteristics under drip irrigation'. *Journal of Drainage and Irrigation Machinery Engineering*, v. 37, n. 2, p. 166-173. DOI: 10.3969/j.issn.1674-8530.17.0047
- Loperfido JV 2014 'Water Quality and Sustainability' in *Comprehensive water quality and purification* pp. 103-121, Ed-in-chef Ahuja S, Elsevier, Amsterdam. ISBN 978-0-12-382183-6



- Miralles, V *et al.* 2013 'A review of heating and temperature control in microfluidic systems: techniques and applications'. *Diagnostics*, v. 3, n. 1, p. 33-67. DOI: 10.3390/diagnostics3010033
- Martins, J Perea 2019 'Introducing the concepts of measurement accuracy and precision in the classroom' *Physics Education*, v. 54, n. 5, p. 055029. DOI: 10.1088/1361-6552/ab3143
- Nxawe, S *et al.* 2010 'Possible effects of regulating hydroponic water temperature on plant growth, accumulation of nutrients and other metabolites'. *African Journal of Biotechnology*, v. 9, n. 54, p. 9128-9134. DOI: 10.5897/AJB2010.000-3336
- Omer, NH 2019 'Water quality parameters', in *Water quality-science, assessments and policy*, Kevin S editor, IntechOpen publisher, DOI: 10.5772/intechopen.89657
- Peng, Hou *et al.* 2021 'Water temperature effects on hydraulic performance of pressure-compensating emitter in a drip irrigation system'. *Irrigation and Drainage*, v. 70, n. 2, p. 332-341. DOI: 10.1002/ird.2547
- Plasquy, Eddy *et al.* 2021 'Estimation of the cooling rate of six olive cultivars using thermal imaging'. *Agriculture*, Vol. 11, no. 2, pp. 164, DOI: 10.3390/agriculture11020164
- Puzdrowska, Patrycja. Determining the time constant using two methods and defining the thermocouple response to sine excitation of gas temperature. *Journal of Polish CIMAC*, v. 11, p. 157-167, 2016.
- Sarnes, B, Schröfer, E 'Determination of the time behavior of thermocouples for sensor speedup and medium supervision'. *Proc. Estonian Acad. Sci. Eng.*, v. 13, n. 4, p. 295-309, 2007.
- Seyedzadeh, Amin *et al.* 2020 'Artificial intelligence approach to estimate discharge of drip tape irrigation based on temperature and pressure. *Agricultural Water Management*, v. 228, p. 105905. DOI: 10.1016/j.agwat.2019.105905
- Thomsen V 1998 'Response time of a thermometer'. *The Physics Teacher*, v. 36, n. 9, DOI: 10.1119/1.880128
- Xu, Feng, *et al.* 2021 'Prediction of fish migration caused by ocean warming based on SARIMA model'. *Complexity*. Vol. 2021, pp. 1-9, DOI: 10.1155/2021/5553935
- Wallard A 2011 'Metrology Principles and Organization', In *Springer Handbook of Metrology and Testing*, Springer Science - Business Media, Berlin Heidelberg), pp. 23-37. ISBN 978-3-642-16641-9