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Article

Desing of a PID controller applied to nutrient flow in a hydroponic system

Diseño de un controlador PID aplicado al flujo de nutrientes en un sistema hidropónico

Hernández-Cervantes, Aldo Aarón*[a], Garciabada-Silva, Gabriel [b], Martínez -Marín, Francisco Alejandro [c] and Cantú-Munguía, Irma Adriana [d]

[a] Tecnológico Nacional de México / Instituto Tecnológico José Mario Molina Pasquel y Henríquez • LTC-5422-2024 • 0000-0001-8060-5509 • 396197
[b] Tecnológico Nacional de México / Instituto Tecnológico José Mario Molina Pasquel y Henríquez • LTE-4156-2024 • 0000-0002-7083-871x • 937809
[c] Tecnológico Nacional de México / Instituto Tecnológico José Mario Molina Pasquel y Henríquez • LTD-3593-2024 • 0000-0002-3713-5182 • 398047
[d] Tecnológico Nacional de México / Instituto Tecnológico José Mario Molina Pasquel y Henríquez • LTE-5228-2024• 0000-0002-1904-421X • 873562

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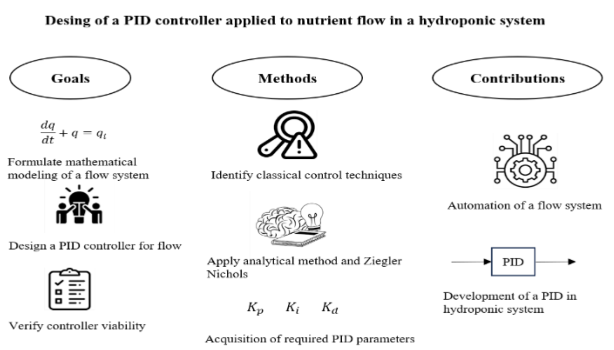
* ✉ [aldo.hernandez@vallarta.tecmm.edu.mx]

Abstract

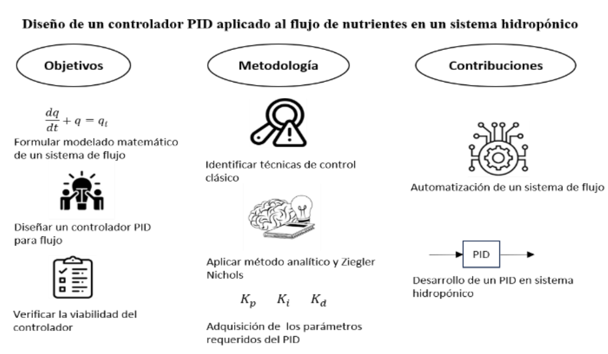
The objective of this article is to carry out a study on the implementation of a PID controller in a flow system coupled to a hydroponic crop with the purpose of maintaining a constant feeding in the. The main reason for applying this type of control lies in the benevolent characteristics whenever it is required, so much so that it is considered a robust controller. In first place, the flow system to be implemented is studied, which consists of a tank provided with nutrients in liquid. In second place, its transfer function is obtained from the characteristic parameters and finally, obtain the design of the controller necessary for the flow of nutrients in a hydroponic system.



Controller, System, Hydroponics

Resumen

El presente artículo tiene como objetivo realizar un estudio sobre la implementación de un controlador PID en un sistema de flujo acoplado a un cultivo hidropónico con la finalidad de mantener una alimentación constante en el cultivo. La principal razón de aplicar este tipo de control radica en las benevolentes características cada vez que es requerido, tanto que es considerado un controlador robusto. Primeramente, se estudia el sistema de flujo a implementar en un tanque provisto de nutrientes en forma líquida. En segundo lugar, se obtiene su función de transferencia a partir de los parámetros característicos y posteriormente, se procede a obtener el diseño del controlador necesario en el flujo de nutrientes en un sistema hidropónico.



Controlador, Sistema, Hidroponía

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Introduction

It is currently known that the development of food crops for the production of industrial products and the misuse of technologies in fertilisation, maintenance and irrigation have caused soil degradation, meaning that thousands of hectares cannot be cultivated (Peña Loredo, 2023). Another resource that must be taken care of is water, as it is an essential part of humanity's daily life and is also the basis for the development of all living beings.

However, of the 70 percent of the planet's surface that is water, only 1 percent of this portion is viable for consumption. A possible solution, which is already being implemented, is the use of hydroponic systems and to carry out the supply of nutrients, control systems are implemented, allowing the recirculation of nutrient-rich water.

In other words, within a hydroponic system it is very important to maintain the nutrients that reach the crop in order to sustain the minimum care to keep the product alive. This task must be carried out periodically and for this purpose, the design of a controller applied to the flow of nutrients with a suitable speed to keep the product fed in the hydroponic system is proposed. The objective of this proposal is justified by the fact that nowadays technological advances can improve, adapt or build a more practical, economical system generating a beneficial and positive impact on the environment.

Theoretical basis

Hydroponic systems are a type of cultivation based on the use of water instead of soil. These types of systems are increasingly used not only by professionals but also by amateurs in urban gardens and indoor crops.

As a background, hydroponics has developed and evolved due to the need to achieve different crops that provide a good quality compared to soil-based crops, making this technique very useful in places with little space such as cities or where it is difficult to have space and soil for crops (Freire & Pujos, 2020).

It is important to mention that in this type of crops it is essential to maintain a correct pH level as well as a balanced level of electroconductivity (EC) in the irrigation water, since a pH imbalance would prevent the correct absorption of certain nutrients, leading to deficiencies in their assimilation. While a too low EC also causes a deficiency in the most important nutrients (nitrogen, phosphorus and potassium); on the other hand, if there is too high an EC it could over-fertilise the plants, completely paralysing their development. In other words, both nutrient deficiency and nutrient excess have a negative effect on the crop (Andrade, 2019).

Table 1 shows the advantages and disadvantages of the use of hydroponic systems in such a way that the great importance of this type of cultivation can be seen.

Box 1

Table 1

Advantages and disadvantages of hydroponic systems

HYDROPONIC SYSTEMS	
Advantages	**Disadvantages**
Less space Faster cultivation Higher yields Fewer pests Cleaner cultivation Environmentally friendly Minimal water use	High initial cost. Basic knowledge of gardening Lack of knowledge of the appropriate system for the specific crop. Lack of knowledge of nutrient management

Own elaboration Control systems

Control systems are those that are governed by control theory, which is an interdisciplinary branch of engineering and mathematics that has also currently added the use of information technologies. In recent years, control systems have become a key element in the development and progress of modern society and technology (González, 2016).

In other words, control systems have played a vital role in the advancement of engineering and science, and have become an important and integral part of modern production processes and any industrial operation that requires the control of temperature, pressure, humidity, flow, level, etc. (Ogata, 1998).

Control systems are concerned with the behaviour and analysis of the dynamics of open-loop or closed-loop systems.

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Open-loop systems are systems where the input is manipulated based on experience with the system, so that the output has the required value; however, the output is not modified by changes in operating conditions. Figure 1 shows the basic configuration of an open-loop control system.

Box 2

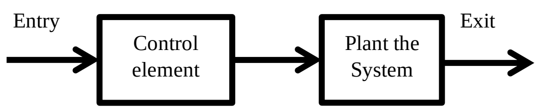

Figure 1
Open loop control system
Own elaboration

Closed-loop systems have feedback to the input from the output, so that a comparison is made, the difference of which is used as a means of control, so that the output remains constant despite changes in operating conditions. Figure 2 shows the basic configuration of a closed-loop control system.

Box 3

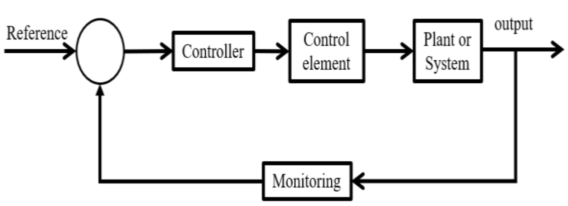

Figure 2
Closed loop control system
Own elaboration

Some advantages of feedback systems are:

- Greater accuracy in matching actual and required values.
- Less sensitivity to disturbances.
- Less sensitivity to component changes.
- High response speed, higher bandwidth.

Controllers

In classical control engineering, a controller is an element that is added to the feedback system and, on receiving an error signal, is capable of providing a control signal that allows a modification to be made to the system with the aim of obtaining a suitable output value (actual value) in accordance with the input parameters (desired value).

In the field of analogue control, the following types of controllers are available.

- Proportional
- Integral
- Derivative
- Proportional-integral
- Proportional-derivative
- Proportional-integral-derivative

Controller design and tuning

In the design and tuning of controllers, there are different ways to carry out this task once the control actions and their possible combinations have been defined. The different methods used are:

- Based on experience (trial and error).
- Ziegler-Nichols adjustment method.
- Reaction curve.
- Pole assignment.
- Frequency design (Bode trace).
- Analytical method

PID controller

Within the classical control techniques there is a controller called PID, which has the characteristic of including in its construction the properties of proportional, integral and derivative controllers. Figure 3 shows a block diagram of the PID controller configuration.

On the other hand, it can be said that a PID controller becomes an important implementation in feedback systems, since this controller has the ability to eliminate steady state errors by means of the integral action, and can anticipate the future with the derivative action. PID controllers are sufficient for solving various problems in process dynamics in different systems.

Box 4

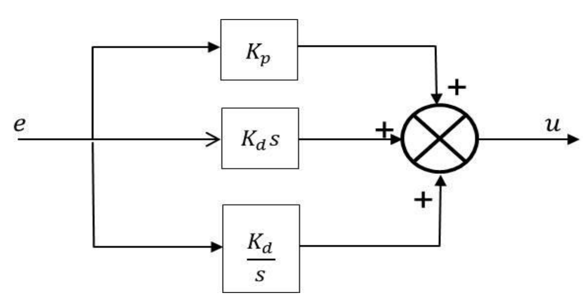

Figure 3
PID controller structure
Own elaboration

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By looking at figure 3, it is possible to obtain the following equation that satisfies the transfer function of a PID controller.

$$G_{PID} = K_p + K_d s + \frac{K_i}{s} \quad (1)$$

However, (1) can also be written as shown in (2).

$$G_{PID} = \frac{K_d s^2 + K_p s + K_i}{s} \quad (2)$$

Which, by presenting a combination of three controllers, it is possible to provide the selection and intensity of the dynamic response of the system from the correct adjustment of the controller gains.

K_p = Proportional gain
K_i = Integral gain
K_d = Derivative gain

Controller design

Analytical method

From the diagram shown in figure 4, which shows all the elements contained in the physical system corresponding to the flow of nutrient-rich water, it is possible to obtain the dynamic modelling necessary for the design of the controller.

Based on the behaviour of the liquid level and flow systems, the following results are obtained:

$$R = \frac{h}{q_0} \quad (3)$$

$$C = \frac{(q_i - q_0)dt}{dh} \quad (4)$$

Box 5

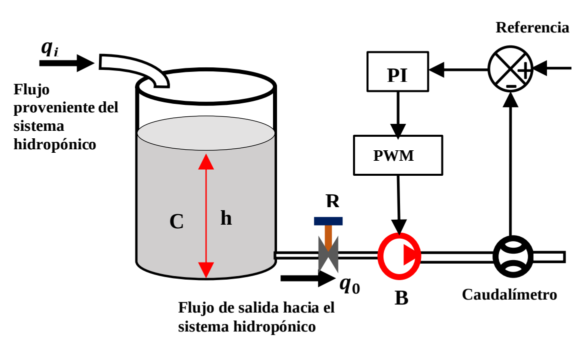

Figure 4
Flow control syste

Where:

C = Tank capacitance
R = Valve resistance
q_i = Tank inlet flow
q_0 = Tank outlet flow
h = Liquid level in tank

Combining (3) and (4) gives

$$RC\frac{dq_0}{dt} + q_0 = q_i \quad (5)$$

Applying the Laplace transform to (5)

$$(RCs + 1)Q_0(s) = Q_i(s)$$

Therefore

$$\frac{Q_0(s)}{Q_i(s)} = \frac{1}{RCs + 1} \quad (6)$$

Where (6) represents the transfer function of the tank used in the nutrient-rich water flow system.

In the case of the pump operating as an actuator it is necessary to consider its proportionality constant, and in this article we choose to represent it by K_B. On the other hand, the flow sensor or flowmeter used is represented by K_s. Where figure 5 shows the open-loop block diagram of the system to be controlled and that subsequently applying the block diagram rules, the required transfer function is obtained and expressed by (7).

Box 6

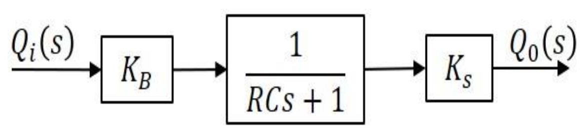

Figure 5
Open loop block diagram of the system
Own elaboration

$$\frac{Q_0(s)}{Q_i(s)} = \frac{K}{RCs + 1} \quad (7)$$

Where

$$K = K_B * K_s \quad (8)$$

K being the gain due to the product of the gain of the pump and the flowmeter. In addition, the time constant (τ) of the open-loop system in the tank is known from the expression (9).

$$\tau = RC \tag{9}$$

Figure 6 shows the block diagram of the feedback system with the controller included. The parameters used in the design of the controller are as follows, which are shown in table 2.

From the table, the values of K_B , K_s , R y C to determine the value of K and τ.

Box 7

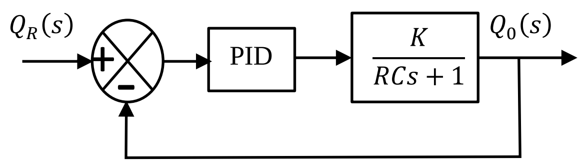

Figure 6
Closed-loop system of the system
Own elaboration

Box 8

Table 2
System parameters

Parameter	Symbol	Value
Resistance (valve)	R	13.34
Tank capacitance	C	0.0725
Pump gain	K_B	1.71
Sensor gain	K_s	2.23
Overshoot	M_P	0.1
Set up time	t_s	5

In this way

$$K = 3.8133$$

$$\tau = 0.967\ s$$

By substituting the values into the block diagram in Figure 6, it is possible to reformulate the diagram as shown in Figure 7 which shows the integration of the PID controller and the plant transfer function of the system to be controlled once the values of its parameters mentioned in Table 2 are known.

Box 9

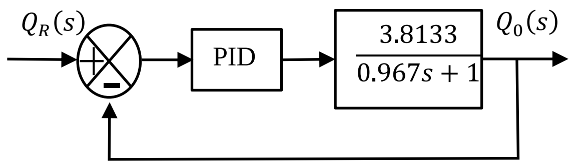

Figure 7
Closed-loop system of the system
Own elaboration

By applying block diagram reduction, the following characteristic polynomial is obtained considering that the PID controller has the form of expression (2).

Therefore

$$(3.8133K_d + 0.967)s^2 + (3.8133K_p + 1)s + 3.8133K_i = 0 \tag{10}$$

If (10) equals it with (11)

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \tag{11}$$

Where:

$\zeta =$ Damping coefficient
ω_n = Undamped natural frequency

According to (Kuo, 1996) the overshoot is determined from the expression (12).

$$M_P = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} \tag{12}$$

By algebraically manipulating expression (12) we arrive at (13) allowing us to know the value of ζ.

$$\zeta = \sqrt{\frac{\ln^2(M_P)}{\pi^2 + \ln^2(M_P)}} \tag{13}$$

Substituting values$\zeta = 0.591$

As the settling time was fixed in table 2, it follows that the expression (14) allows to know the value of ω_n.

$$t_s = \frac{4}{\zeta\omega_n} \tag{14}$$

In other words

$$\omega_n = \frac{4}{\zeta t_s} \tag{15}$$

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Substituting values

$$\omega_n = 1.3536 \,{}^{rad}/_{seg}$$

Once it is known ω_n y ζ, et is possible to find the values of K_p, K_d y K_i by equating the coefficients of expressions (10) and (11)

$$3.8133K_d + 0.967 = 1 \quad (16)$$

$$3.8133K_p + 1 = 2\zeta\omega_n = 1.5972 \quad (17)$$

$$3.8133K_i = \omega_n^2 = (1.3536)^2 \quad (18)$$

Substituting values for the coefficients, the gains of the PID controller are known:

$K_p = 0.1566$
$K_i = 0.4805$
$K_d = 0.00865$

Método Ziegler-Nichols

This method focuses on a closed-loop system where the controller is located in the direct system path. In the case of the system proposed in this article, obtaining the required controller starts by taking the transfer function of the system described by the expression (19)

$$G_s = \frac{3.8133}{0.967s + 1} \quad (19)$$

Applying a delay (θ) of 3 seconds due to unforeseen dynamics in the system, the transfer function referring to the Padé approximation is shown in expression (20).

$$G_p = \frac{\frac{2}{\theta} - s}{\frac{2}{\theta} + s} \quad (20)$$

Furthermore, substituting θ=3 gives the required Padé approximation.

$$G_p = \frac{\frac{2}{3} - s}{\frac{2}{3} + s} \approx \frac{0.667 - s}{0.667 + s} \quad (21)$$

Figure 8 shows the block diagram of the system using Padé's approximation. (G_p), the system flow system transfer function of the system (G_S) and the required driver (K_{ZN}), which is to be determined.

Box 10

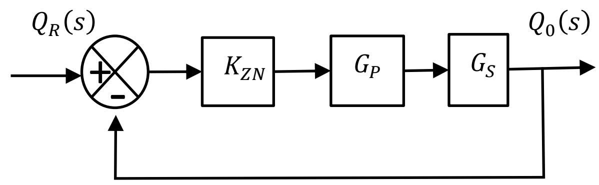

Figure 8
Block diagram taking into account Padé's approach

Own elaboration

From the diagram shown in Figure 8, the transfer function of the system by substituting its values is given in equation (22). Where, in addition, the characteristic polynomial of the system expressed in equation (23) is obtained.

$$\frac{Q_0(s)}{Q_i(s)} = \frac{(2.54 - 3.8133s)K_{ZN}}{0.967s^2 + (1.645 - 3.8133K_{ZN})s + 0.667 + 2.54K_{ZN}} \quad (22)$$

$$0.967s^2 + (1.645 - 3.8133K_{ZN})s + 0.667 + 2.54K_{ZN} \quad (23)$$

As part of obtaining the controller parameters, the first step is to work with the imaginary part equal to zero if $s = i\omega$

$$1.645 - 3.8133K_{ZN} = 0$$

$$1.645 = 3.8133K_{ZN}$$

Therefore

$$K_{ZN} = 0.4311$$

Being K_{ZN} the maximum gain (K_U) required to know part of the controller parameters from the Ziegler-Nichols method.

As a second step, the real part is taken and equalised to zero if $s = i\omega$

$$-0.967\omega^2 + 0.667 + 2.54K_{ZN} = 0$$

$$0.967\omega^2 = 0.667 + 2.54K_{ZN}$$

$$\omega^2 = \frac{0.667 + 2.54K_{ZN}}{0.967}$$

$$\omega = \sqrt{\frac{0.667 + 2.54K_{ZN}}{0.967}}$$

Substituting the value of K_{ZN} the value of the maximum frequency (ω_U)

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$\omega_U = 1.35$

And as the maximum period (P_U) se is determined from the expresión (24)

$$P_U = \frac{2\pi}{\omega_U} \quad (24)$$

Then by substituting the value of the frequency, the value of the period is known.

$P_U = 4.654$

Once the values of K_U and P_U Table 3 is used in order to know the required parameters for a PID controller.

Box 11

Table 3

Tuning by the Ziegler-Nichols method

Parameter	Controller		
	P	PI	PID
K_P	$\frac{K_U}{2}$	$\frac{K_U}{2.2}$	$\frac{K_U}{1.7}$
τ_i		$\frac{P_U}{1.2}$	$\frac{P_U}{2}$
τ_d			$\frac{P_U}{8}$

Table 3 shows the parameters required for a controller depending on the type to be used.

From table 3 it is then known that

$K_P = 0.253$
$\tau_i = 2.327$
$\tau_d = 0.58$

Where

K_P = Proportional gain
τ_i = Integration time
τ_d = Derivative tense

These being the parameters of a PID controller justified by the expression (25)

$$G_{PID} = K_P\left(1 + \frac{1}{\tau_i s} + \tau_d s\right) \quad (25)$$

Results

Simulation tools are used to simulate the calculations obtained in each of the methods used to obtain the PID controller parameters.

Figure 9 shows the block diagram of the system that serves as a reference to obtain the results of the simulation when using the analytical method when there is an input flow of $3\ {}^{l}/_{min}$.

Box 12

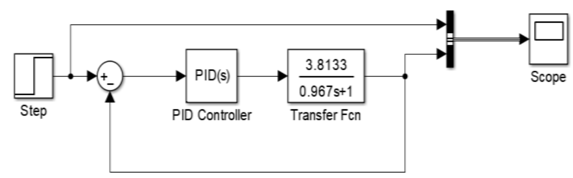

Figure 9

Block diagram analytical method implemented in simulink

Figure 10 shows the simulation graph of the system when applying a PID controller obtained by the analytical method from knowing its parameters of over impulse and settling time.

Box 13

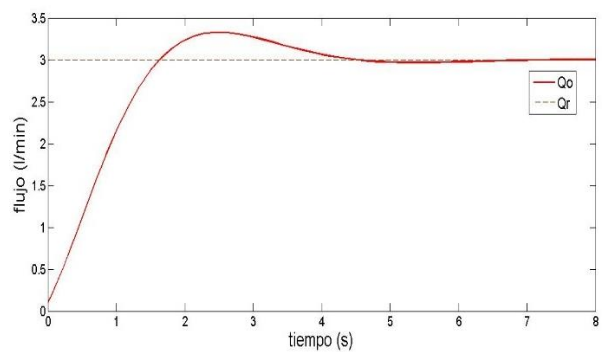

Figure 10

Plot of the system implementing analytical PID

Own elaboration

From figure 10 it can be seen that the system response shows a settling time of 4 seconds and an over-peak of 10 percent over the reference value.

In the case of the Ziegler-Nichols method used to obtain the PID, figure 11 shows the system response with a smoother response. However, the settling time is approximately 2 seconds slower than the analytical method and also this PID causes a negative response due to the zero contained in the first order Padé approximation.

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Box 14

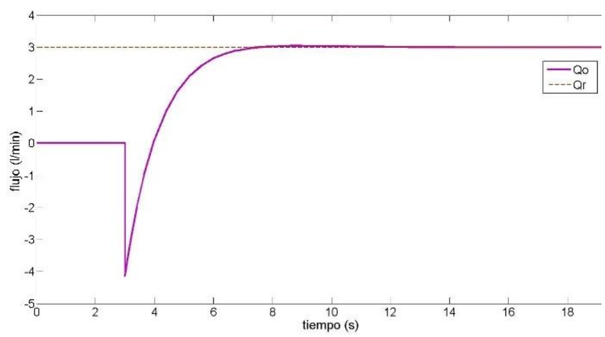

Figure 11
Plot of the system implementing analytical PID

Own elaboration

Conclusions

This article deals with the design of a PID controller for a nutrient-rich water flow system for a hydroponic crop. The proposal was to show two methods to obtain the controller, being an analytical method considering the over-peak and the damping factor. The second method focused on using the Ziegler-Nichols method by coupling a first-order Padé approximation to the system.

Once the simulations and results are obtained, it is identified that the best option for this flow system is the implementation of a PID found in the analytical method.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest. They have no known competing financial interests or personal relationships that could have influenced the article reported in this paper.

Authors' contribution

Hernández-Cervantes, Aldo Aarón: contributed with the development of the mathematical models, design of the controller by the analytical method, as well as writing the article.

Garciabada-Silva, Gabriel: I contributed with the analysis and calculations of the parameters of the supply system to the hydroponic system.

Martínez-Marín, Francisco Alejandro: His contribution was the development of the controller based on the Ziegler-Nichols method.

Cantú-Munguía, Irma Adriana: Her contribution was to review sources of information and support the idea for this project, as well as helping with the revision of the article.

Availability of data and materials

The availability of data and materials are those that were collected throughout the development of the project.

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Abbreviations

EC	Electroconductivity
pH	Hydrogen Potential
PID	Proportional-integral derivative

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Background

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