Chapter 1 Food Area

PROTOTYPE HYDROPONIC SYSTEM WITH LED LIGHTING CONTROL AND PARAMETER MEASUREMENT FOR VARIOUS HORTICULTURE CROPS

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Abstract

Among the main challenges that future generations will face is the scarcity of food and the lack of space for its cultivation. Hydroponics is an agricultural technique that is based on the independence of plants from the soil, since it uses only water as a means of transporting the substances and nutrients that crops need for their proper development, increasing efficiency and reducing the time in which crops are ready for harvest. In addition, the implementation of alternative lighting systems that allow the growth of plants without depending on solar illumination, being the use of LEDs one of the most popular and with the best results. This work describes the design process of a prototype hydroponic system with LED lighting control and measurement of parameters (temperature, pH, conductivity and dissolved oxygen) for various horticulture crops.

1. Introduction

Agriculture is a fundamental part of the Mexican economy, accounting for 4 % of GDP in 2024 [1]. According to a projection study carried out by the National Population Council (CONAPO), it is estimated that Mexico will have a population of 138.1 million inhabitants by 2030 and 148.2 million by 2050 [2]. This population increase is directly related to the main challenge that agriculture will face in the coming years: ensuring food supply for the population. Demographic expansion coincides with the decrease in land available for agriculture, and it is therefore predicted that by 2050, only 0.16 ha of arable land will be available in the country to produce the food demanded by one person per year, compared to 0.27 ha per person in 1980 and 0.18 ha in 2015 [3].

In addition to the country's supply capacity, the environmental and biological problems present in the crops that affect their availability must be taken into consideration. According to the latest data collected by the National Institute of Statistics and Geography (INEGI), in 2017 there were 32,406,237 hectares in the country destined to agricultural production units, performing open-air agriculture. Of this total, 21 % (6,810,762 hectares) correspond to irrigated surface, while the remaining 79 % (25,595,475 hectares) correspond to rainfed surface. Of the 101,828 production units surveyed, only 17,388 used protected agriculture production strategies, the majority of which were of the greenhouse type (54.1 %). On the other hand, among the main problems presented during the development of activities in the production units, crop losses due to climatic causes (74.7 %), crop losses due to biological causes (44.2 %) and loss of soil fertility (28.4 %) stand out. It should be noted that among the main reasons for crop losses due to climatic causes are wind, excess humidity, hail, low temperatures and floods [4].

The environmental impact of agricultural development must also be taken into account. In terms of water availability and use, in Mexico in 2015, a total volume of water concessioned in the country of 266,569 million cubic meters was determined. Of this amount, it is estimated that 32.2% had a consumptive use. Of the consumptive use, more than 3 quarters was used for agricultural purposes, with a percentage of 76.3%, with costs per cubic meter of water ranging between $2.49 MXN and $78.67 MXN depending on the area in which it was obtained. Of the total amount of water used for agriculture, only 46 % is used efficiently [5]. In addition, agriculture represents the largest proportion of human land use and is a major source of emissions of gases that contribute to the greenhouse effect, such as methane (CH_4), nitrous oxide (N_2O) and to a lesser extent, carbon dioxide (CO_2) [6].

As highlighted in the national agricultural planning 2017-2030 conducted by the Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA), trends in food and agriculture should focus on technological development and innovation seeking new triggers in production systems [7]. The main strategies for increasing agricultural production should focus on improving yield per unit area and increasing the cultivated area [3].

This paper describes the design process of a prototype hydroponic system with LED lighting control and parameter measurement for vegetables. The prototype was developed with the intention of using it as a research and experimental tool, with the objective of comparing the results of growing crops of the same species under different lighting conditions. The development of hydroponic crops considers supplying the nutrients required by the plants through water, without the need of any substrate. In addition, the illumination received by the plants was controlled by means of light-emitting diodes (LEDs) with different wavelengths to compare their effect on plant growth. Finally, a graphic interface was implemented that, with the help of sensors located in the prototype, allows the user to visualize the history of some physical and chemical parameters (temperature, pH, conductivity and dissolved oxygen) in which the crop has been found. This prototype is intended to serve as an auxiliary in the promotion and development of new technologies for more efficient crop production in the country.

2. Methodology

Figure 1 shows a block diagram of the prototype. The system is composed of three main units, the physical design of the prototype, the circuit that is responsible for polarizing the LED light sources and sensors and monitoring the signals generated by the latter, and finally the control circuit of the luminous intensity of the LEDs.

2.1. *Case*

A case was built with four divisions, taking into account that the dimensions of each space will be determined by the maximum expected dimensions of the growth of each specimen of each plant, in this case the selected vegetables were lettuce and beans. Based on work done with lettuce under similar conditions, i.e., with LED lighting and applying hydroponics as an agricultural technique, measurements were obtained after 35 days of testing on lettuce specimens with a maximum width of 12 cm and a height no greater than this measure [8]. On the bean side, the height can reach 28 cm in a growth period of 30 days [9]. Based on these two measures, it was decided to take as a basis the maximum width that lettuce plants could have and the maximum possible height of bean plants. This led to establish 30 cm x 12 cm x 24 cm as design parameters for the internal dimensions of the prototype. Considering that in each space of the prototype a lettuce specimen and a bean specimen will be placed, each plant will have a total volume for its development of 4320 cm^3 considering dimensions of 12 cm x 12 cm x 30 cm. It was decided to design a structure that allows each space to have the dimensions proposed and that isolates each space from the outside so that the light irradiated in each one is the desired one and that allows the correct oxygenation of the plants.

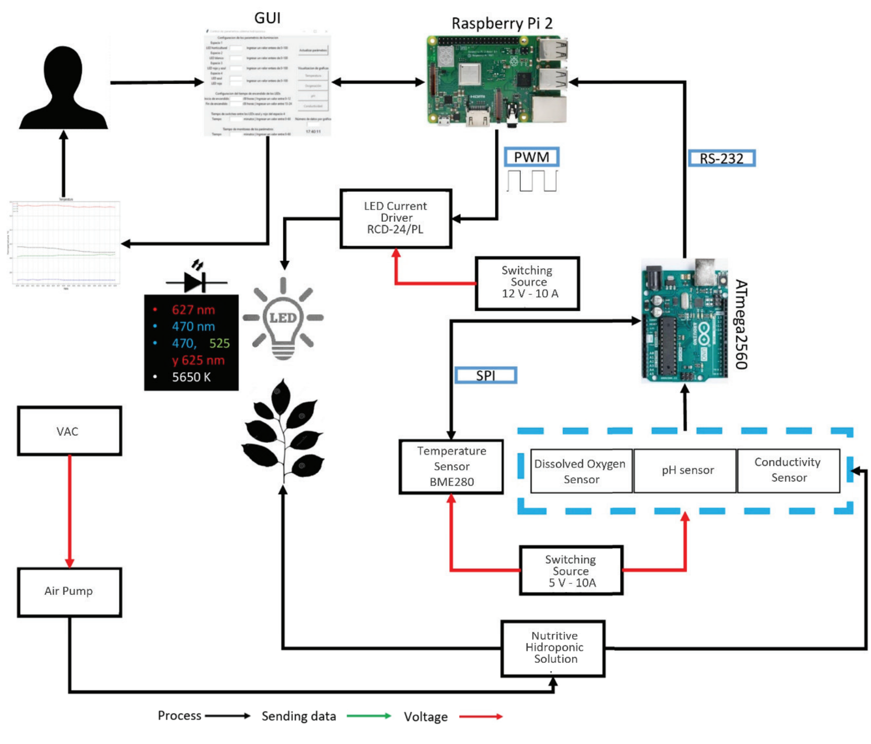


Figure 1. Block diagram of the developed system.

Figure 2 shows graphically how the prototype is physically constituted in a general way, in gray color the structure of each space is observed while in black color the water tank of the whole system is observed. The walls of each space are made of acrylic with a thickness of 3 mm, where each wall will have eyebrows that allow the assembly of these under pressure.

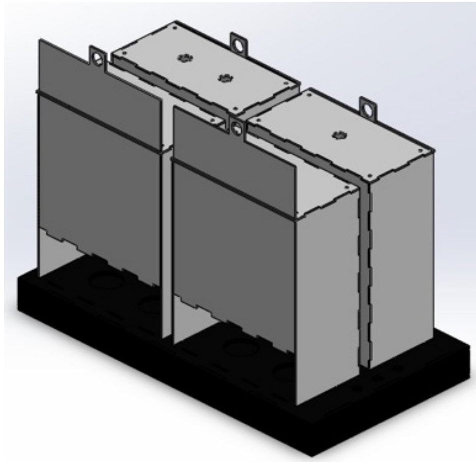


Figure 2. Representation of the physical design of the prototype.

The prototype must have the capacity to store at least one specimen of each crop to be analyzed in each of the 4 spaces destined for the comparison of the effects of the wavelengths of the LEDs, with one or two LEDs in each space as the case may be (see Table 1), these crops correspond to lettuce and beans.

Type of LED	Wavelength (nm)
Red	627
Blue	470
Multicolor (blue, green and red)	470, 525 y 625
White	400-700

Table No. 1 Types of LEDs used and their wavelengths.

2.2. *Graphical User Interface (GUI)*

As shown in Figure 1, the operation of the GUI consists of filling in all the input fields where the parameters for LED illumination intensity, LED on/off time, switching time between blue and red LEDs, update time for monitoring the parameters acquired from the sensors and the maximum number of data to be stored in the graphs are established. The GUI programming has default parameters set so that if the user does not enter data, the system can function when the program is run. However, when entering data by filling in the input fields and executing the "Update parameters" button, the default values are updated to the values entered by the user, modifying the operation of the system. The buttons for displaying graphs remain disabled at startup until sensor data acquisition begins, when there is at least one data value, the graphs of the desired parameters are displayed.

Since the characteristics of the Raspberry Pi used as the main control element prevent it from reading analog signals and the oxygenation, pH and conductivity sensors handle signals of this type, it was decided to include an additional microcontroller as an intermediary for the sensor signals. The microcontroller chosen was the ATmega328P (Microchip Corp.), which is responsible for reading the sensor signals to send the corresponding data to the Raspberry Pi via serial communication. The choice of this microcontroller is due to the fact that it has the necessary interface for the acquisition of analog signals; in addition, using this platform reduces the cost and facilitates the assembly with respect to other options. For this reason, the programming of the Raspberry Pi includes the creation of a serial object, which is read to obtain the values of the sensors. For its part, a program was developed with the ability to interpret the signals from the sensors and send the corresponding values of these through serial communication.

2.3. *Sensors*

In order for the user to be able to observe the specific parameters for the water of each hydroponic crop (oxygenation, pH and electrical conductivity) and their correct measurement, it was decided to also take measurements of the oxygenation, pH and electrical conductivity in the water of the crops; for this, the sensors to be used were DFRobot® brand sensors, specifically the SEN0161 (pH), DFR0300 (electrical conductivity) and SEN0237-A (oxygenation) models. These sensors have a connector that converts the output signal of the measured parameter into an analog signal that will be interpreted by the controller to be used; which avoids a previous signal conditioning stage, also in its physical design the part of the sensor that needs to be in direct contact with the water has a length of up to 26 mm, with a diameter of up to 13 mm, which allows measurements in shallow water tanks [10].

In the case of sensors that are in direct contact with water: pH, conductivity and oxygenation sensors, based on their dimensions, a minimum depth of 13 mm and a diameter of 26 mm is necessary for them to have support and be able to perform measurements correctly. These characteristics were considered in the design by placing three holes with a diameter of 30 mm in the part corresponding to the water tank lid, and since the tank has a depth of 4 cm, it was only necessary to insert the sensors in these holes in order to carry out the measurement, as shown in Figure 3.

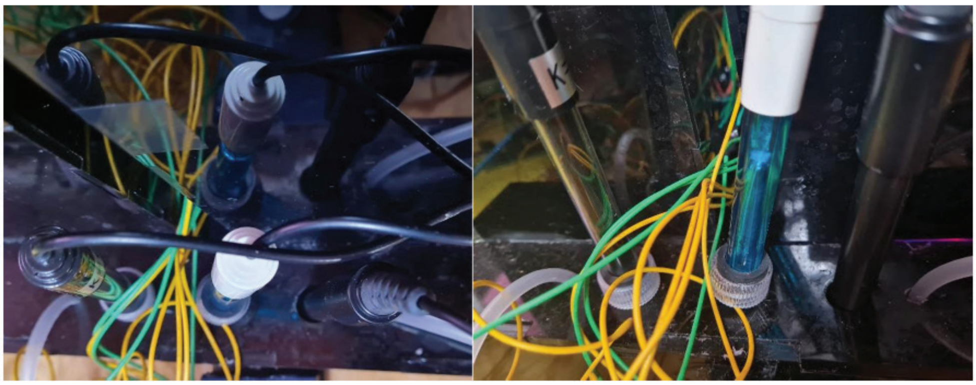


Figure 3. Mounting of pH, conductivity and oxygenation sensors in the prototype´s water tank.

Additionally, it was determined that in order to define the conditions in which each crop was according to the light conditions, it was necessary to measure the temperature in each space, so the BM280 sensor (Adafruit Industries) was used, which is a temperature sensor that uses the SPI communication protocol. On the other hand, to vmaintain better oxygenation of the water in the prototype tank, two water pumps in the fish tanks were used.

2.4. *Assembly of hydroponic baskets*

In the case of the hydroponic baskets, the space they would occupy was determined from the design stage of the acrylic pieces, locating two circles of 5 cm in diameter that were distributed uniformly in the spaces in each corresponding area for the development of crops, so it was only necessary to introduce the hydroponic baskets in the holes intended for this purpose as shown in Figure 4.

Figure 4. Assembly of the hydroponic baskets in the prototype.

2.5. *Crop germination*

The germination process of lettuce and bean crop seeds was carried out independently of the system, initiating germination in specialized phenolic foam for hydroponics, the procedure involved saturating the foam by immersing it in water until fully moistened, subsequently, bean and lettuce seeds were positioned within the foam, and the container was covered to maintain humidity. To expedite germination, twenty-four bean and 24 ball-type lettuce seeds were deployed, as depicted in Figure 4A. Once the specimens had germinated and developed their initial leaves, they were transferred to the hydroponic system. Figure 4B shows the germinated crop specimens.

A)

B)

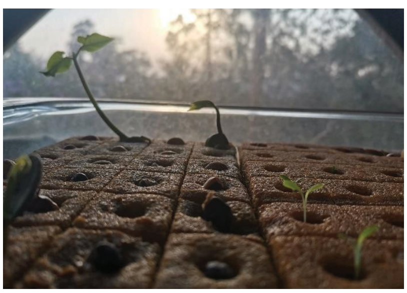


Figure 4. (A) Placement of bean and lettuce seeds for germination in phenolic foam for hydroponics and (B) Germination of the cultures in the phenolic foam.

The preparation of the solution consists of a process where, in addition to adding nutritive salts from the Semillas de amor® brand to the water to be used, parameters such as pH and conductivity must be adjusted.

	Parameters	
	pH	Conductivity (mS/cm)
Pure water	7.1	0
Solution after adding nutritive salts	3.0	2.14
Solution after adjusting pH with 0.5 M solution of NaOH	5.5	2.27

Table 2. Parameters of the nutritive solution.

Epura® brand bottled water was selected, according to a study carried out with different brands of bottled water in Mexico [11], this is the brand that presents the lowest concentration of total dissolved solids (TDS) with 9 ppm and calcium with a value of less than 20 mg/L. The importance of maintaining a low value in this concentration lies in the fact that in order to optimize the efficiency of the nutrient solution, the pH and conductivity parameters must be controlled, and these values are modified when nutritive salts are added to the water. The appropriate parameters to optimize the efficiency of the nutrient solution are between 5.5 and 6.5 in the case of pH [12], and between 1 and 3 mS/cm for conductivity [13]. When measuring the bottled water, pH values of 7.1 and conductivity of 0 mS/cm were obtained; however, when the mineral salts were added, the pH value was reduced to 3.0 while conductivity increased to 2.14 mS/cm. In spite of complying with an adequate conductivity value, the pH value was very low; for this reason, 8 milliliters of a sodium hydroxide (NaOH) solution with a concentration of 0.5 mol/L were added to the nutrient solution to increase the pH, obtaining after this process a pH value of 5.5 and a conductivity of 2.27 mS/cm, complying with the adequate values in the solution parameters. Table 3 shows a concentration of these data.

With the elements assembled and working in the prototype, the GUI implemented in the Raspberry Pi and the nutrient solution with the appropriate parameters, the system was put into operation in order to validate its operation. For this, one lettuce and one bean species were introduced into the prototype for each space of the system, as shown in Figure 5, and the parameters were set in

Parámetro	Set Value
Luminous Flux of LEDs	75%
Turn-on Hour of LEDs	08:00
Turn-off Hour of LEDs	22:00
Switching time between Blue and Red LEDs in block 4	30 min
Acquisition time of sensors parameters	5 min
Points per graph	30

Table 3. Conditions established for system tests.

the GUI for its operation: all LEDs were set to an illumination power of 75 % of capacity, 14 hours of continuous illumination were set, turning on the LEDs at 08: 00 hours and turning them off at 22:00, a switching time between LEDs of space 4 was set, in addition to a sensor parameter acquisition time of 5 minutes and an amount of data per graph of 30, these values are concentrated in Table 3.

Figure 5. Implementation of the germinated crops in the prototype.

3. Results

At the end of the implementation stage and with the device in operation, the operation of the system was validated and the results were concentrated. 21 days after placing the germinated cultures in the system for their development, their growth was analyzed. Figure 6 shows photographs of the crops in the system; it should be noted that, due to problems with the low germination rate of beans, only 3 specimens could be obtained; for this reason, only lettuce was placed in the space with intermittent blue and red LED lighting.

A)

B)

C)

D)

Figure 6. Crops under different sources of illumination: A) Constant with blue and red LEDs, B) Constant with LED Horticultural, C) Constant with white LEDs and D) Intermittent with blue and red LEDs.

It stands out the fact that the crops where the highest growth was obtained were with constant illumination of blue and red LEDs in the case of beans, and with intermittent illumination of blue and red LEDs in the case of lettuce. The lowest performance for both bean and lettuce was with white illumination. The data corresponding to the length of each crop and the number of leaves developed are shown in Table 4.

Type of LED	Crop	Length (cm)	Number of leaves
Blue and Red	Lettuce	30	8
	Beans	2	4
Horticultural	Lettuce	21	5
	Beans	2	5
White	Lettuce	4.5	3
	Beans	1.5	4
Blue and Red Modulated	Lettuce	3	4

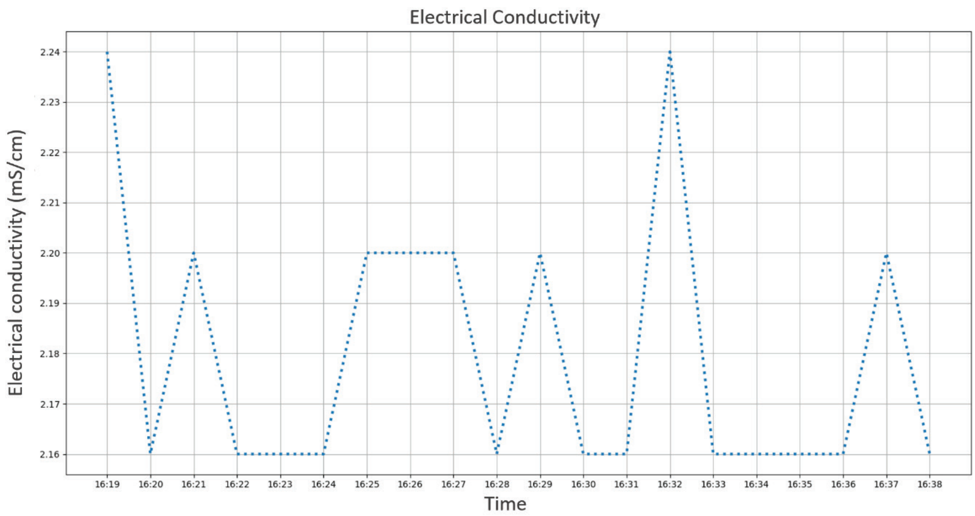
Table 4. Conditions established for the system tests.

While, for beans, the minimum temperature during its growth phase is 10 °C [14], in the case of lettuce, the optimum temperature during this phase is considered to be 14 - 18 °C. This may explain the reason for the poor growth of lettuce so far, due to the fact that in the area where this practice is being carried out, during the winter period, the maximum temperature does not exceed the temperature range for optimal lettuce growth. It should be noted that although the prototype is capable of measuring the temperature, it does not have any actuator element that can modify it.

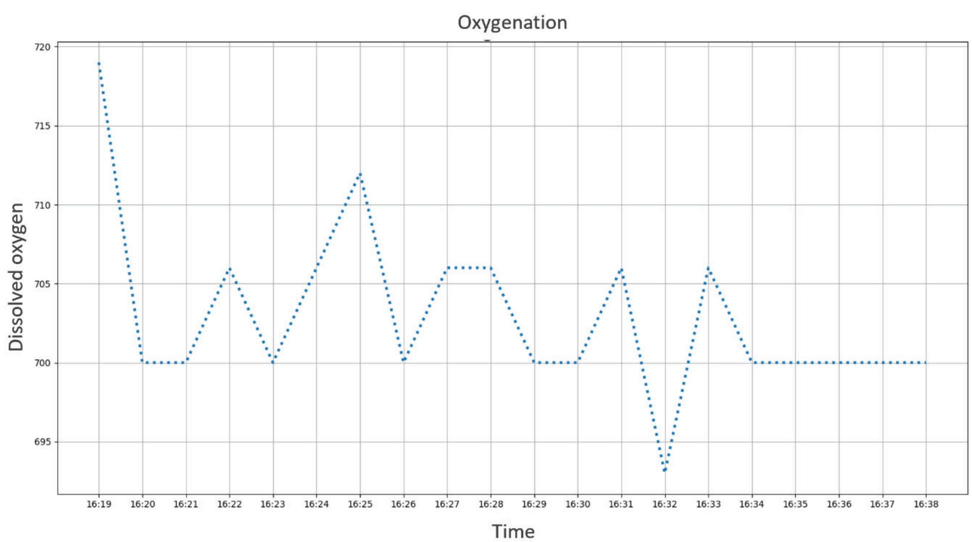
With the system running and the operating parameters configured through the GUI, it was verified that the sensors were working properly and that the interface was capable of storing the acquired data for later visualization. Performing a test for 20 minutes, where values of all parameters were stored every minute, the graphs shown in Figure 7 were obtained.

As can be seen in some graphs, the parameters remain constant over time, the variations are minimal, with a variation of 3.7 % for conductivity, 3.6 % for oxygenation, 1.2 % for pH and a percentage of less than 1 % in the temperature values; and these are only affected considerably after hours in the case of temperature and days in the case of conductivity and pH, in the case of oxygenation the values depend on the operation of the water pumps.

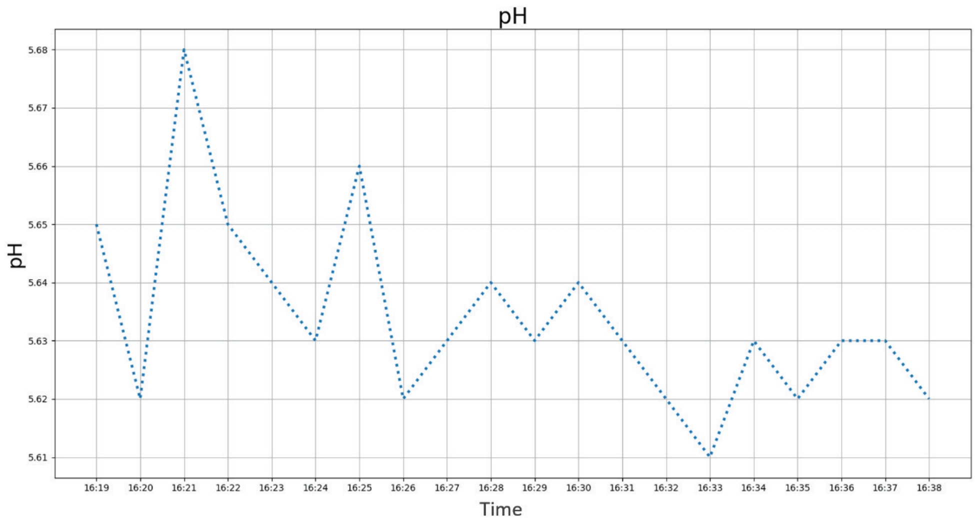
A)


Electrical Conductivity
Electrical conductivity (mS/cm)
2.24
2.23
2.22
2.21
2.20
2.19
2.18
2.17
2.16
16:19 16:20 16:21 16:22 16:23 16:24 16:25 16:26 16:27 16:28 16:29 16:30 16:31 16:32 16:33 16:34 16:35 16:36 16:37 16:38
Time

B)


Oxygenation
Dissolved oxygen
720
715
710
705
700
695
16:19 16:20 16:21 16:22 16:23 16:24 16:25 16:26 16:27 16:28 16:29 16:30 16:31 16:32 16:33 16:34 16:35 16:36 16:37 16:38
Time

C)



D)

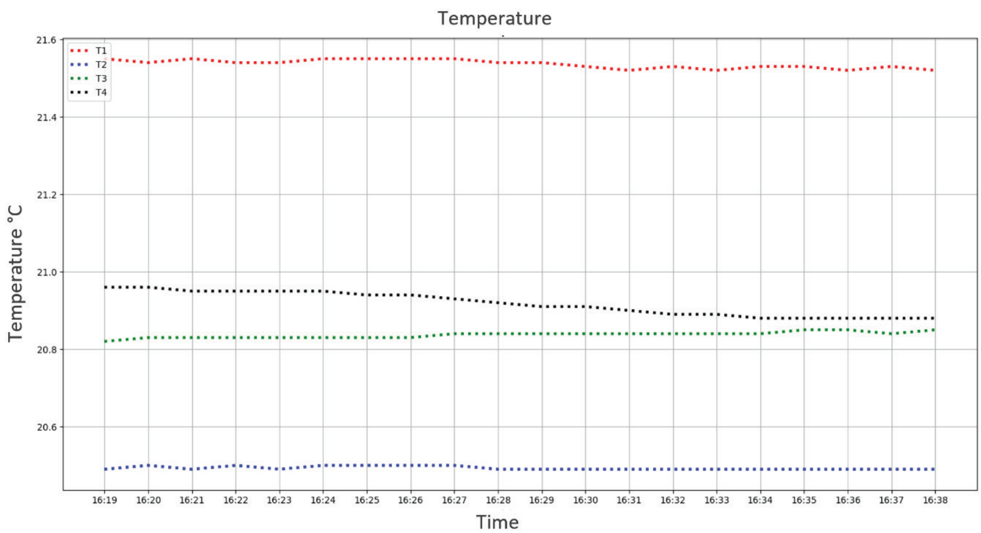


Figure 6. Behavior of: A) electrical conductivity, B) dissolved oxygenation in water, C) water pH and D) temperature.

4. Conclusions

In this work a prototype of a functional hydroponic system was developed, which allows the development of crops while it is possible to monitor chemical parameters such as pH, and physical parameters such as electrical conductivity, which depends on the concentration of salts, and oxygen dissolved in the water. The system provides the user through a GUI the possibility to configure the conditions to operate automatically in the data acquisition times of the sensors, the amount of stored data of the parameters, the switching times between LEDs and the on and off of the LEDs, allowing to set the intensity of illumination required. In addition, the data obtained from the different measured parameters can be displayed graphically in the GUI.

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