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Control of an aquaponic system to improve the yield of gray tilapia and lettuce cultivation

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ABSTRACT

Water quality assessment presents challenges, primarily the paucity of available data and ongoing system maintenance. This research develops an automated monitoring and control of water quality parameters in aquaponic systems with internet of thing (IoT) technology. Proper fish feeding management is important, which is why the fish were fed at 12:00, 16:00 and 07:00. The most significant relative error recorded during the validation of the DS18B20, PH-4502C, SEN0244, SEN0237-A, SEN0189 and DFR0300 sensors is 5.0%. The maximum standard deviation between the mentioned sensors was 1.96, and the highest coefficient of variation reached 7.24%. Before the installation of the aquaponic system, the specific growth rate (SGR) of fish was 4.89±0.17% and after implementing the automated aquaponics system, the SGR of fish increased to 6.21±0.24%. The feed conversion ratio values of the fish, both before and after the installation of the control system, were 1.98±0.14% and 1.53±0.09%, respectively. In addition, an improvement in plant growth was observed, evidenced by the difference in the values of height, number of leaves, leaf length, and weight of the plants before and after the installation of the control system, which was 7.74 cm, 5 leaves, 5.6 cm, and 41.6 g respectively.

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1. INTRODUCTION

The progressive reduction of agricultural land is attributed to various current trends, such as population growth, urbanization, drastic environmental changes, decreasing water supply and challenges in food security [1]. Therefore, the current paradigm highlights the urgency of researching new agricultural methodologies. In this context, the aquaponic cultivation methodology emerges as a promising solution to increase agricultural productivity [2]. Aquaponics represents an integrated food production system, combining hydroponics, a method of growing plants without soil, with aquaculture, which is the raising of aquatic animals such as fish [3]. Allowing various fundamental interactions between the different components of the system, including fish, plants, nitrifying bacteria such as *nitrosomonas* and *nitrobacter*.

The latter are responsible for transforming the ammonia produced by fish into essential nutrients for plants, which by absorbing it improve their performance when growing [4], providing many advantages over traditional agriculture, since they require less water, land and fertilizers, minimizing the waste [5].

However, factors such as the filtration system, water flow and aeration, as well as the type of fish and plants grown, can regulate the main aquaponics system [6], to avoid abnormal variations in dissolved oxygen values (DO), ammonia (NH3, NH4+), nitrite (NO_2-), salinity, electroconductivity (EC), potential hydrogen (pH), temperature and turbidity [7]. These variations impact water quality and therefore the growth rate of crops, ultimately causing their death due to poor water quality management [8]. This is why the introduction of automation, intelligent strategies and connectivity is viable for the management of complex aquaponic systems that require specific skills and complex tools [9]. As demonstrated by research by Qin and Mardi [10], simply knowing and recording water pH and temperature data in aquaponics systems can improve the system's ability to address problems by more accurately identifying their causes and offering effective solutions. Another research carried out by Mansor *et al.* [11] implemented a monitoring and data recording system that, through an Android device and a web server, allowed viewing the conditions of fish and plants in aquaponic systems, based on the internet of thing (IoT) to control temperature, humidity, pH levels and water pumps through microcontrollers. However, these studies do not fully analyze some fundamental parameters for water quality since they focus mainly on temperature and pH, resulting in this information being insufficient for a comprehensive evaluation of the aquaponic system, since changes in water quality occur quickly and if one element is out of sync, the entire system could directly threaten crop growth and mortality. Furthermore, there are studies in which, despite analyzing a greater number of parameters, the benefits offered by the application of technologies compared to traditional methods in crop development are not mentioned, as is the case of the study carried out by Kok *et al.* [12] who used a PIC18F4550 microcontroller to analyze 5 parameters and focused only on the control responses. Another case is the study carried out by Autos *et al.* [13] where the Arduino Mega was used to control the aquaponic system and 7 parameters were analyzed, but it only focused on the control of the parameters. For this reason, this study evaluates the impact of an aquaponic monitoring system on the growth and health of lettuce (*Lactuca sativa var. crispa*), which is the vegetable in greatest demand, and gray tilapia (*Oreochromis niloticus*), which can adapt to different environments [14], analyzing the control of water quality parameters such as temperature, pH, total dissolved solids (TDS), dissolved oxygen, turbidity, flotation and electroconductivity, and their impact on crop development.

2. MATERIALS AND METHOD

The Raspberry Pi 4B is a microcomputer used in this study to collect data, process information, and transmit signals to the actuator. The Raspberry Pi 4B was selected because it has better performance, compatibility, better processor, multimedia support, uses low battery consumption, and works over wireless fidelity (Wi-Fi) [15]. The programming language used will be Python 3.10 with which the optimal operating values will be programmed. The number of metrics to monitor also influences the quality and cost of the developed monitoring system [16]. In cases where the values of the monitored parameters are different from the values established as optimal, Raspberry will send a control signal to the corresponding actuators to regularize said parameters in time. Among the sensors used we have the following: a temperature sensor (DS18B20), which allows temperatures between -55 °C to 125 °C, with a precision of ±0.5 °C, powered by a voltage of 3 to 5 V; a pH sensor (pH-4502C), which allows measurement of pH in a range of 0 to 14 powered from 3.3 to 5.5 VDC; a total dissolved solids sensor (SEN0244), which allows measurement of ranges from 0 to 2000 ppm using an operating voltage of 3.3 to 5.5 CVV; a dissolved oxygen sensor (SEN0237-A), having a detection range of 0~20 mg/L, with an operating voltage ranging from 3.3~5.5 V and an analog output signal that is between 0~3 V [17]; also a turbidity sensor (SEN0189) and float sensor (ZP5210) and the conductivity sensor (DFR0300). As can be seen in Figure 1, among the actuators that respond to a control signal we have a mini water pump (AD20P-1230A) DC 12 V of 4.2 W with a flow rate of 240 L/H, a recirculation pump of water (Resun SP3800), 2 syringe pumps for pH that are activated by stepper motors (28byj48) that have a nominal voltage between 5 and 12 V and insert pH if the value is lower than desired or a basic substance if the value is greater than the established one, 2 Peltier's (TEC1-12706) which has an operating voltage of 0-12V and an operating current of 0-6A to heat or cool the water in the tank and an air pump to oxygenate the water from the Resun-ACO brand from China with a power of 18 W. Finally, there is a 7" thin film transistor-liquid crystal display (TFT LCD) that allows the Raspberry Pi to display the average values of temperature, pH, total dissolved solids, dissolved oxygen, turbidity, float sensor, and the state of the actuators on the Raspberry Pi conductivity. All these sensor values can also be viewed and stored in the Firebase or in the application, which can display the actuator's on or off time.

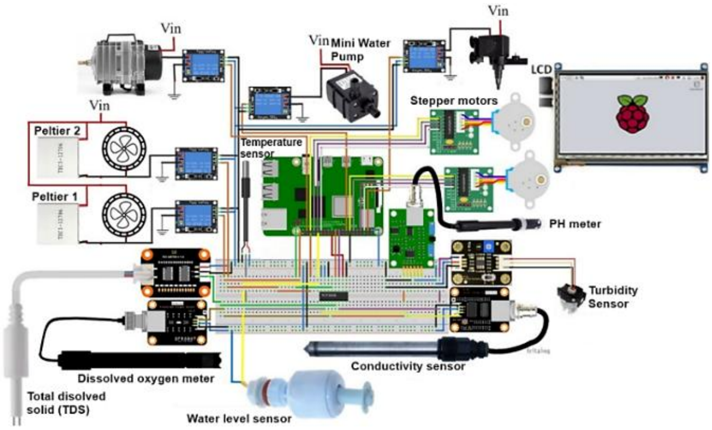


Figure 1. General circuit that will be integrated into the aquaponic system

2.1. Description of system operation

By programming the system with the conditions detailed in Figure 2, the system can continuously monitor water quality parameters. In turn, it activates the actuators to adjust the values. These values are configured from the application where the intervals for each parameter are established. Once the “OK” button is pressed, the values will be sent to the Raspberry Pi 4 to be stored in the form of variables, which will be used to compare with other values obtained in each sensor, depending on what you want to achieve, the activation can be conditioned. or not of the actuators. If the DS18B20 sensor detects a temperature lower than 26 °C to 29 °C, it can be heated with the first Peltier, and if it is a higher temperature, it can be cooled with the second Peltier. If the water level is below the minimum set level, the recirculation pump will automatically activate to raise the normal water level [15]. If the PH-4502C detects that the pH is outside the normal range of 6.5 to 8.0, it will be regulated by dripping alkaline (pH increasing solution) or acidic (pH decreasing) into the main container using the pH syringe pumps [18]. The recirculation pump will activate if the TDS value is above 1,200 ppm and will deactivate when the value decreases to 900 ppm. In the same way, the recirculation pump will maintain the turbidity in the range of 15 to 22 NTU, activating when the turbidity value is above the maximum value and turning off when the minimum value is reached. The air pump will be activated only if the dissolved oxygen value is less than 5 mg/L, until it reaches its normal value of 8.5 mg/L [19]. High EC levels suggest contamination in the water and may result in fish population mortality. However, a minimum or optimal salt content of 1,000 to 1,500 µS/cm is better as it helps fish maintain an osmotic balance, maintaining maximum nutrient use without the need to over-fertilize. If it is higher, the mini water pump will be activated, otherwise, the basic pH syringe will be activated to maintain the EC level at 1,250 µS/cm [20]. All of these measurements mentioned will be stored in Firebase and will be viewed through the mobile application.

2.2. System architecture

As shown in Figure 3, the aquarium tank is made of plastic that contains 30 liters of water, has a cylindrical shape, and dimensions of 35 cm in radius and 40 cm in height. Above the tank, some polyvinyl chloride (PVC) tubes have circular holes with a radius of 4 cm, in which the lettuce plants are located, and at the base, it has other holes for the entry of water with nutrients. These PVC pipes are stacked on the tank containing the tilapia so that the bell siphon drains the pumped water back to the tank through a closed circuit. The water pump, which is located at the bottom of the tank, from its position pumps water containing the fish waste to the top through the pipes, where the nitrifying bacteria responsible for transforming this waste into nutrients are located, which the lettuce will later use. Thus, decreasing the level of ammonia produced by fish excretion, which in turn decreases the mortality of the fish population [21]. The increase in temperature in the pond causes toxicity levels to increase, causing greater production of ammonia and other nitrogenous compounds. That is why the Peltier is used to control the temperature, through the use of a heat sink connected to two hoses, in which one is in charge of extracting the water and the other of returning cold water to keep the pond at an ideal temperature. The 18 W Resun-ACO, an air pump from the city of Shenzhen in China, was used to achieve an adequate air drop of 4 to 8 liters per minute for small-scale systems [22]. At the bottom, next to the aquaponic tank, you can see two syringe pumps for pH, one loaded with acid solution and the other with alkaline solution, each one has a motor that step by step will activate and go forward or backward back injecting the solutions into the water to load the syringe of 3 cm in diameter and a volume of 60 ml. If the pH value of the aquaponic tank is higher than established, an alkaline solution will be injected, and if it is lower, an acidic solution will be injected. The fish waste enriched with ammonia remains deep in the aquaponic tank, which is taken to biofilters through water pumps, where nitrifying bacteria decompose the ammonia into nitrates and nitrites that are used by plants as nutrients. Subsequently, after filtering all the water, it is recirculated again to the aquaculture tanks safely, thus being a closed circuit [23]. The biofilter contains a filter medium with a porous texture, through which water and bacteria that require good aeration pass. This biofilter is a cylindrical tank located above the two syringe pumps for pH [24]. To monitor and alert changes in the levels of the variables, the aquaponic system collects information from the variables through the device's sensors, in the form of temperature, turbidity, pH, dissolved oxygen, TDS, ammonia, and level of water in the pond. Through the microcomputer, the data received by the sensors will be analyzed using the program created in Python, and then the IoT technology will be used to send to the cloud server, for registration and user interface [25]. Thus, allowing the grower to continuously monitor and evaluate the status of the pond from a great distance in real time as shown in Figure 3. Additionally, these values will be displayed on a TFT LCD screen connected to the Raspberry Pi 4.

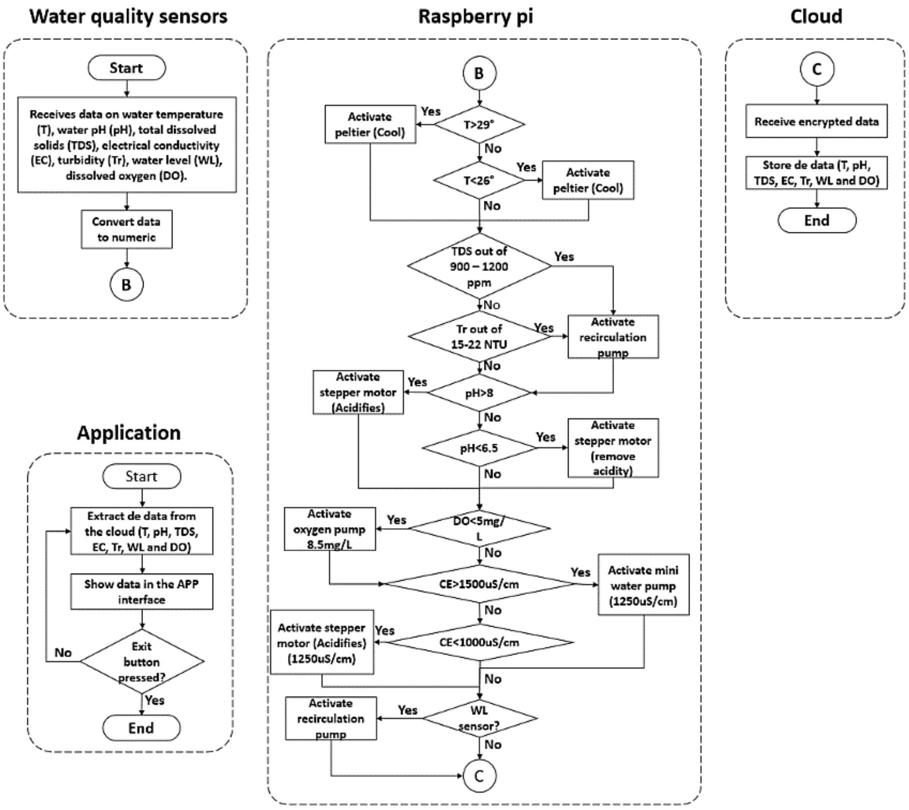


Figure 2. System programming flowchart

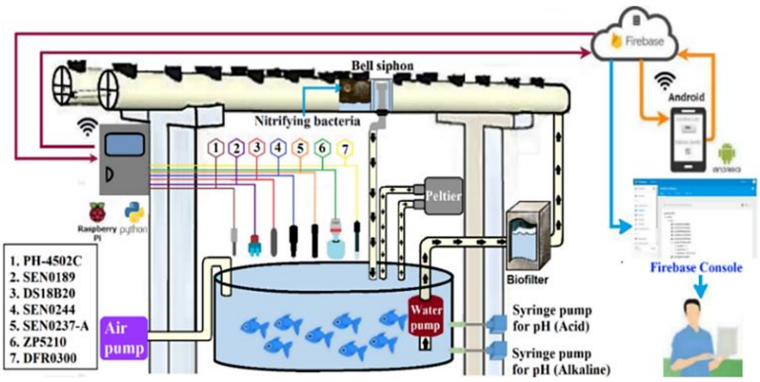
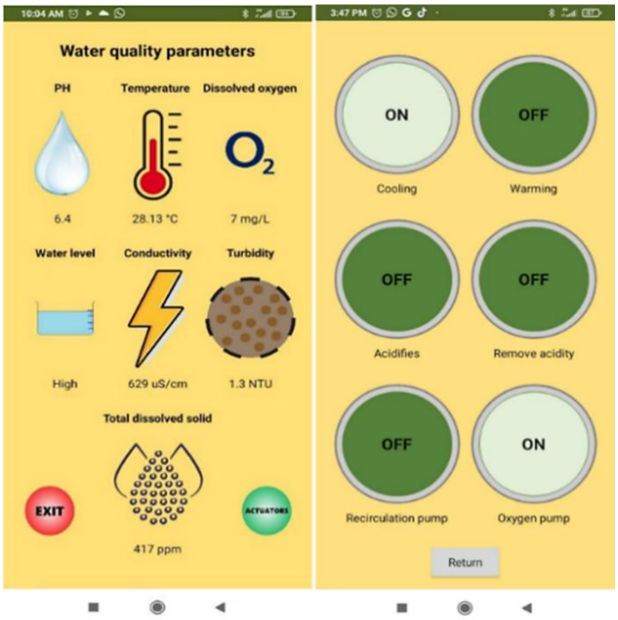


Figure 3. Architecture of the automated aquaponic system

2.3. Android application for hydroponic growing

The Android application for hydroponic cultivation shown in Figure 4. This application has an interface to display the water quality parameters, which are obtained through the sensors of the aquaponics system as shown in Figure 4(a) and with an interface to verify the status of the actuators as shown in Figure 4(b). Through the message queuing telemetry transport (MQTT) protocol, this application will allow you to monitor the system remotely by extracting information from the sensors and sending it to the Firebase. The data that will be stored in it can be viewed through a JSON file that is synchronized with end users or Android-based mobile applications in real-time and will be updated every 5 seconds [26]. In addition, the operation of the actuators can be viewed through the application, making it possible to turn them on and off remotely as long as the aforementioned conditions are respected.



(a) (b)

Figure 4. Application of the aquaponic system: (a) sensor values and (b) status of the actuators

2.4. Experimental procedure

The calibration process of the sensor node was started using certified industrial equipment, through comparisons the precision of the sensors of the aquaponics systems was calculated. Once the system was automated, 30 lettuce seedlings were grown, which had specific characteristics with a height of 5 and 7 cm, and several leaves between 4 and 5. The roots of the lettuce seedlings were cleaned with distilled water before cultivation, each one was wrapped in a sponge and then placed inside a glass that was introduced into the PVC tubes of the system. For fish selection, 40 tilapia that were in the fry stage were chosen. After this, data on the growth of plants and fish were recorded, before and after the automated aquaponic system was installed to compare them [27]. In the case of tilapia, every fourth night through random sampling, the weight was measured with a Mettler Toledo ML204T/00 analytical scale and the growth length was measured using a tape measure, to evaluate the weight gain (WG), the specific growth rate (SGR), the feed conversion ratio and the survival rate that were calculated with (1) to (4) respectively.

$$Weight\ gain\ (g) = final\ weight\ (g) - initial\ weight\ (g) \tag{1}$$

$$Specific\ growth\ rate = \frac{(\ln final weight\ (g) - \ln initial\ weight\ (g))}{time (No. of\ days) \times 100} \tag{2}$$

$$Feed\ conversion\ ratio = \frac{feed\ intake\ (dry\ weight)(g)}{body\ weight\ gain (wet\ weight)(g)} \tag{3}$$

$$Survival\ rate\% = \frac{total\ number\ of\ harvested\ fish}{total\ number\ of\ initial\ stock} \times 100 \tag{4}$$

The characteristics of the lettuce were measured to analyze its growth. In the case of the lettuce, its height and length were measured with a measuring tape; its weight was calculated in grams each week that had passed, with which the growth rate of the lettuce was calculated. These measurements were carried out during the 4 weeks that the experimentation lasted.

2.5. Sensor calibration

Precision represents a fundamental factor that influences the performance of each measuring instrument. For this reason, in this research the standard deviation, the relative error and the coefficient of variation were used. These statistical tools will guarantee the reliability of the results obtained and thus detect possible errors in the data collected.

2.5.1. Standard deviation

Standard deviation is a measure of dispersion in a data set, showing how dispersed the data is around the mean, allowing us to evaluate the consistency and precision of the data. The standard deviation obtained in each test carried out allows us to know the precision of the samples. This can be calculated using (5).

$$\sigma_x = \frac{\sqrt{\sum_{i=1}^{n}(x_i - x)}}{(n-1)} \quad (5)$$

Linearity is closely related to the proportionality of input and output. The calibrated sensors in this monitoring device are: pH, water temperature, electroconductivity, TDS, temperature and humidity sensors [28]. This calibration improves the precision of the measurements.

2.5.2. Relative error

Relative error is a measure that indicates the precision of a measurement, in this case it is presented as the difference between the sensor readings and the actual value. It is measured expressed in percentages of the real value as shown in (6). This equation indicates that the smaller the relative error value, the more accurate the sensor will be [29].

$$RE = \frac{|Measured\ value - Real\ value|}{Real\ value}(100\%) \quad (6)$$

2.5.3. Coefficient of variation

The coefficient of variation is a statistical measure that provides a measure of the variability of the data relative to its average size. Useful results to compare the dispersion of the different variables [30]. This can be calculated using (7).

$$Coefficient\ of\ variation = \frac{\sigma}{\mu} \quad (7)$$

where σ is the standard deviation and μ is the mean

3. RESULTS AND DISCUSSION

A significant difference (P<0.05) was found in the performance of the fish after 4 weeks of rearing in the aquaponic system. The tilapia raised in the aquaponic system reached higher values in weight gain and average final length, as shown in Table 1. It reached values of 5.74±0.24 g in weight and 4.53±0.16 cm in length. On the other hand, in the traditional aquaponics system, values of lower weight gain and final average length were obtained, these were 4.09±0.21 g and 3.34±0.15 cm respectively, as shown in Table 2. In comparison to the survival rate in the traditional and automated aeroponic system, this showed a survival rate of 97.5%, while the traditional system showed a survival rate of 85%, as shown in Tables 1 and 2. Furthermore, it can be seen in these tables that the automated aquaponic system showed the best results since it obtained 1.53±0.09 feed conversion ratio (FCR) and 6.21±0.24% SGR compared to the traditional system which obtained 4.89±0.17%.

As evident in Figure 5, there is a significant difference in the variable height of the lettuce seedling. The aquaponic system with the control system obtained better results with an average height of 19.91 cm, compared to the absence of the control system, since the figure was lower, reaching an average height of 12.17 cm. This is a considerable difference, which is a good indicator of the functioning of the aquaponic system.

As shown in Figure 6, during the 4 weeks of cultivation, the number and length of lettuce leaves could be analyzed. The results show that due to the control system applied to the aquaponic system, an average of 17 leaves per plant and 25.8 cm in leaf length were obtained. This is superior to the results obtained without the application of the aquaponic system, where an average of 12 leaves per plant and 20.2 cm of leaf length was obtained. Figure 7 shows the significant differences in the weight of lettuce after transplanting lettuce seedlings. The average weight with the application of the automated aquaponic system was 176.4 g of fresh weight, while without using the system, the maximum average value was 134.8 grams. The weight variation was greater during the fourth week.

Table 1. Growth data of red tilapia fingerlings in an automated aquaponic system

Week	Wo	W(t)	Total weight of food	Initial length (cm)	Final length (cm)	Specific growth rate	FCR	Survival rate
1	1.08±0.05	1.72±0.10	33.6g	0.59±0.13	1.46±0.06	6.21±0.24%	1.53±0.09	100%
2	1.72±0.10	2.96±0.07	52.8	1.46±0.06	2.31±0.24			100%
3	2.96±0.07	4.49±0.06	88.6	2.31±0.24	3.46±0.07			97.5%
4	4.49±0.06	5.74 ±0.24	135.6	3.46±0.07	4.53±0.16			97.5%

Table 2. Growth data of red tilapia fingerlings in a traditional aquaponic system

Week	Wo	W(t)	Total weight of food	Initial length (cm)	Final length (cm)	Specific growth rate	FCR	Survival rate
1	1.04±0.08	1.58±0.13	0.58±0.04	1.16±0.16	32.7 g	4.89±0.17%	1.98±0.14	92.5%
2	1.58±0.13	2.15±0.06	1.16±0.16	1.84±0.28	51.6 g			92.5%
3	2.15±0.06	3.04±0.16	1.84±0.28	2.53±0.09	68.8 g			87.5%
4	3.04±0.16	4.09±0.21	2.53±0.09	3.34±0.15	94.3g			85%

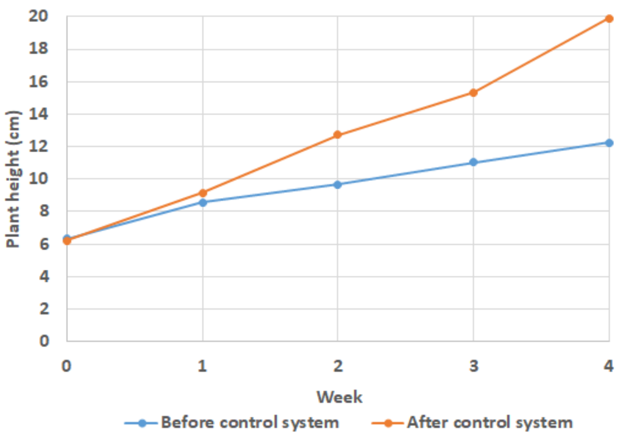


Figure 5. Plant height before and after the automated aquaponic system

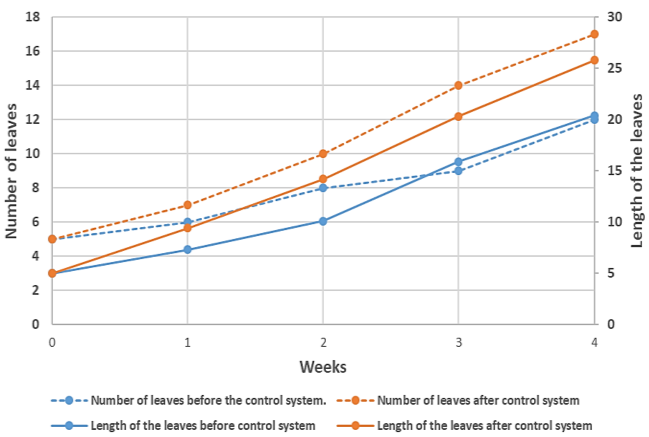


Figure 6. Number of leaves before and after the automated aquaponic system

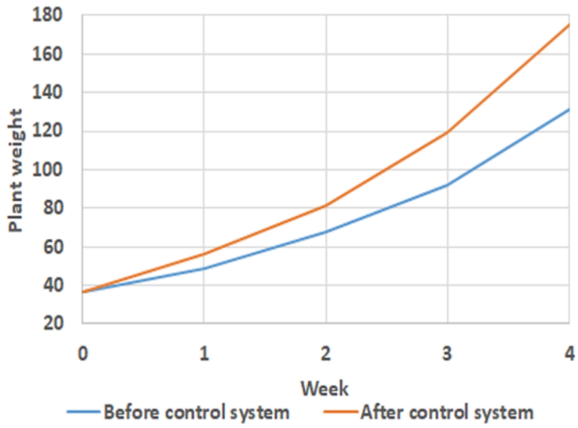


Figure 7. Plant weight before and after the automated aquaponic system

3.1. Sensor calibration analysis

Through the repeatability method, the precision of the process or system is obtained. This involves carrying out repeated measurements of the same magnitude under identical conditions using the same measurement system and with the same operator. In this case, the tests for each sensor were carried out at different intervals and quantities. Using 4 different measurements in the water (5 °C, 10 °C, 30 °C, and 40 °C), with the mercury thermometer that has the most accurate capacity to measure temperature, the calibration process of the DS18B20 sensor was carried out and each one was measured 10 times. As can be seen in Table 3, the values obtained, the standard deviation, the coefficient of variation, and the relative error of the DS18B20 sensor are shown.

Table 4 shows the pH test values using the HANNA instrument-HI98129 and the PH-4502C sensor. 4 different pH values were obtained from the pH sensor calibration using the "pH liquid buffer instrument." These values were analyzed to evaluate the accuracy and consistency of the calibrated sensor.

To measure the values of electrical conductivity and TDS, instruments such as the Conductivity solution 1,413 µs/cm were used to calibrate the HANNA - HI98129 at a liquid temperature of 25 °C. Thus, allowing a comparison of the values obtained for electrical conductivity and TDS, using the DFR0300 and SEN0244 sensors respectively. Tables 5 and 6 show the values obtained when measuring four different types of water, the standard deviation, the coefficient of variation, and the relative error of the SEN0244 and DFR0300 sensors, respectively.

With the MW600 dissolved oxygen meter using 4 different measurements of the dissolved oxygen level and performing 10 different measurements in the water (5.3, 9.42, 13.94, and 18.37 mg/L) the calibration of the SEN0237-A sensor was carried out. Table 7 shows the values obtained, the standard deviation, the coefficient of variation, and the relative error of the SEN0237-A sensor. It can be seen that the highest relative error is 3.51 and the highest standard deviation is 0.85.

As shown in Table 8, comparisons were made of the values obtained through the Bante TB 100 turbidimeter and the SEN0189 sensor. These values were obtained by testing with the TN500-S1 standard turbidity calibration solution. Thanks to these comparisons it was possible to calculate the relative error, standard deviation and coefficient of variation of the sensor.

Table 3. Table of water temperature results in the calibration test

Water temperature	Mercury thermometer	DS18B20 average	Standard deviation	Coefficient of variation (%)	Relative error (%)
5	5	5.17	0.40	1.93	3.40
10	10	10.21	0.19	1.86	2.10
30	30	30.50	0.74	1.54	1.67
50	50	50.48	0.16	0.31	0.9675

Table 4. Table of results of the pH level in the calibration test

pH liquid buffer	HANNA - HI98129	PH-4502C average	Standard deviation	Coefficient of variation (%)	Relative error (%)
4.01	4.01	4.1925	0.71	7.24	4.55
5	5	5.0375	0.39	3.85	0.75
7	7	7.31625	0.82	1.65	4.52
10.01	10.01	10.05875	0.28	2.55	0.49

Table 5. Table of results of the TDS level in the calibration test

Liquid	HANNA - HI98129 (ppm)	SEN0244 (ppm) average	Standard deviation	Coefficient of variation (%)	Relative error (%)
Distilled water	52.6	54.02	1.06	1.96	2.70
Drinking water	128.4	126.97	1.63	1.29	1.1
Drum water	176.1	178.82	2.23	1.24	1.54
River water	1236	1241.31	1.94	0.16	0.42

Table 6. Table of results of the electrical conductivity level in the calibration test

Liquid	HANNA - HI98129 (µS/cm)	SEN DFR0300 (µS/cm) average	Standard deviation	Coefficient of variation (%)	Relative error (%)
Distilled water	105.3	108.9125	1.79	1.64	3.43
Drinking water	247.1	248.0625	1.91	0.77	0.38
Drum water	328.6	329.7875	1.90	0.57	0.36
River water	2381.4	2436.7	1.96	0.08	2.32

Table 7. Table of results of the level of dissolved oxygen in the water in the calibration test

MW600 dissolved oxygen meter	SEN0237-A average (mg/L)	Standard deviation	Coefficient of variation (%)	Relative error (%)
5.3	5.42	0.85	1.84	2.26
9.42	9.60	0.38	1.87	1.91
13.94	14.43	0.29	1.73	3.51
18.37	18.58	0.37	1.23	1.14

Table 8. Table of results of the turbidity level in the water in the calibration test

TN500-S1 turbidity standard calibration solution	TB 100 Bante turbidimeter (NTU)	SEN0189 average (NTU)	Standard deviation	Coefficient of variation (%)	Relative error (%)
0.02	0.02	0.021	0.00024	1.10	5
20	20	20.45	0.33	1.61	2.25
100	100	101.36	0.73	1.132	1.36

3.2. Measurement of variables using the aquaponic system

As shown in Figure 8, the water temperature is taken and recorded every 30 minutes. Below is an example of water temperature trends during November 8 and 9: the highest temperature was 28.74 °C at 2:00 p.m. on November 8 and the lowest was 26.08 °C at 00:00 hours on November 9. The difference between the temperatures was 2.88 °C, being around the optimal range of 26 °C to 29 °C for the red Nile tilapia. Furthermore, due to the activation or deactivation of the Peltier when the temperature varies outside the allowed ranges, you can see how the temperature dropped at 2:00 p.m. and increased at 00:00.

Figure 9 shows the pH values obtained during November 8 and 9, taken at each hour of the day. It was obtained that the highest pH record occurred at 5:00 p.m. with a pH of 7.92 on November 8 and the lowest pH record occurred at 8:00 a.m. with a pH of 6.74 on November 9. In the following graph, you can see a decrease from 5:00 p.m. to 5:00 a.m. due to the activation of the pH-base syringe pumps due to a pH level greater than 8.

The turbidity values obtained during November 8 and 9 are shown in Figure 10. We can see that the highest turbidity record was 21.87 NTU at 4:00 p.m. on November 8 and the lowest record was 3:23 p.m. NTU at 3:00 p.m. on November 9. With the activation of the recirculation pump, we can notice a decrease in the Turbidity level starting at 4:00 p.m., because the SEN0189 sensor detected a measurement greater than 22 NTU. This pump stabilized the turbidity level up to approximately 15 NTU and became regular as seen in the graph.

As shown in Figure 11, dissolved oxygen (DO) does not vary significantly due to the resting state of the fish. However, the linear relationship between temperature and DO can be denoted, since at higher temperatures the variation of DO increases, and likewise, at lower temperatures it decreases. On the other hand, the DO presents an abrupt drop when the fish feed, because it is the time of greatest locomotion. Thus, it is confirmed that as the fish move, the water temperature is affected together with the concentration of DO in the water. The activation of the air pump occurred satisfactorily, avoiding the abrupt decrease in the DO in the water below 5 mg/L. This activation occurred at 2:00 p.m. and 10:00 p.m. on November 8 and at 7:00 a.m. on November 9, as shown in Figure 11.

As can be seen in Figure 12, the electrical conductivity (EC) ranged between 1,200-1,500 µS/cm, maintaining its appropriate range for the good development of the lettuce. The adjustment of the EC in the nutrient solutions was carried out by activating the minipump and activating the injection of the base pH, which simultaneously reduced the EC value. In both cases, deactivation was scheduled when the EC reached 1,250 µS/cm as a set point. The greater activity of the fish at the feeding times, which are at 12:00 and 16:00 on November 8 and 7:00 on November 9, significantly increased the EC concentration because these produce greater waste. Thus, obtaining a maximum value of 1,492 µS/cm and a minimum of 1,258 µS/cm. Furthermore, it can be seen that the lower the temperature, the smaller the change that occurs in the EC. The maximum and minimum value obtained in this graph is 1,492 µS/cm and the lowest is 1,258 µS/cm respectively.

As can be seen in Figure 13, it can be seen that the TDS fluctuated within the programmed range of 900-1200 ppm, which is considered optimal to promote good lettuce development. In case of a fluctuation outside the normal ranges, which normally increases significantly when the fish feed at 12:00 and 16:00 on November 8 and 7:00 on November 9, the recirculation pump will be activated until the optimal value of 900 ppm is reached. Furthermore, it is notable to observe the abrupt changes in TDS, which reflect the modulation of the level towards 900 ppm.

As an initial test of operation and performance, the sensor node measures the response time of each sensor, collecting detailed information on individual performance. Being essential to guarantee the precision and reliability of the monitoring system. Figure 14 shows that the DO measurement consumes the most time, taking an average time of 1.28 s for each measurement and sending cycle. On the other hand, the average time taken by the pH and turbidity sensors is approximately 1 s. While the EC sensor takes approximately 1.3 s, the temperature and TDS sensors take approximately 8.83 and 7.05 s respectively.

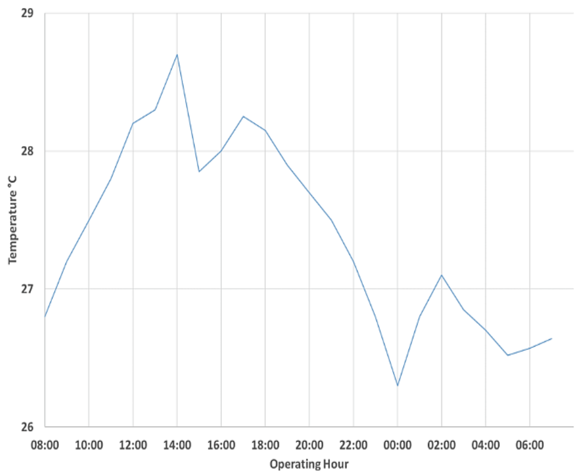


Figure 8. Water temperature reading

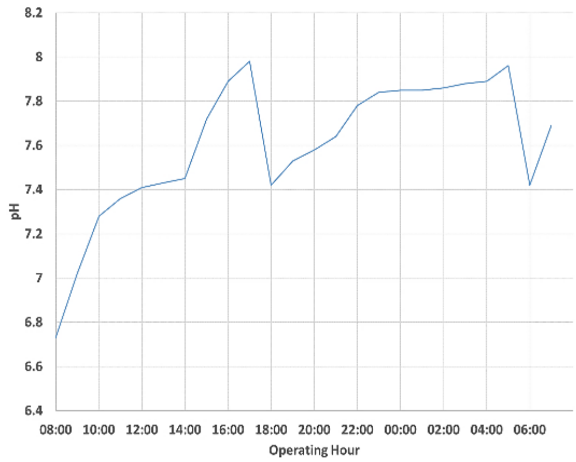


Figure 9. Water pH reading

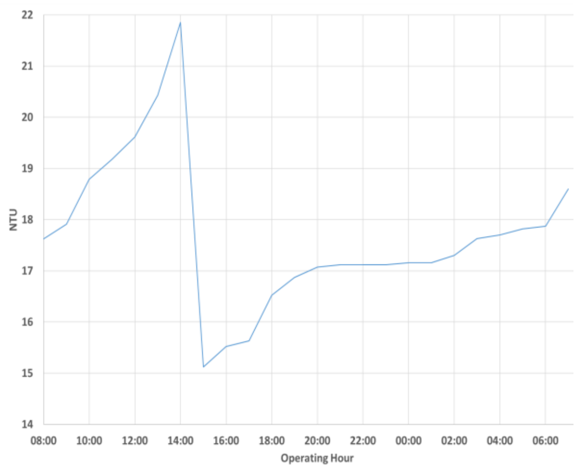


Figure 10. Water turbidity reading

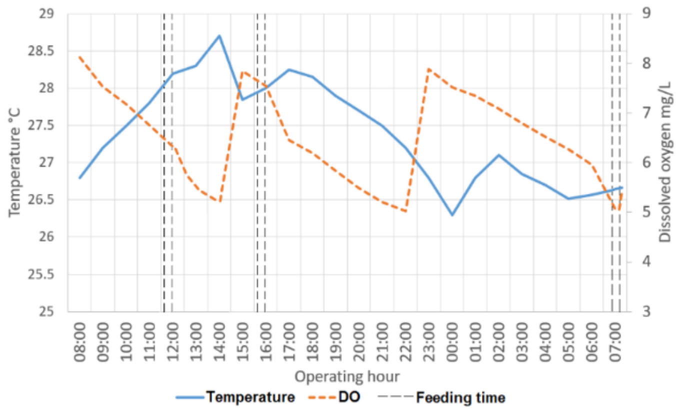


Figure 11. Dissolved oxygen level vs water temperature

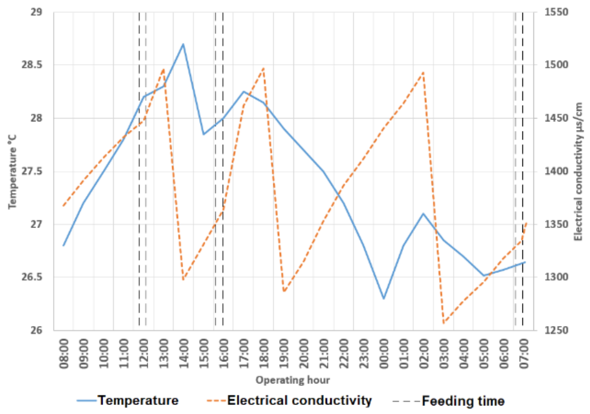


Figure 12. Electrical conductivity level versus water temperature

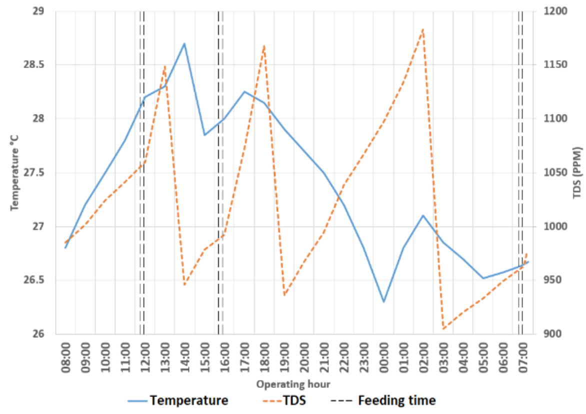


Figure 13. TDS level versus water temperature

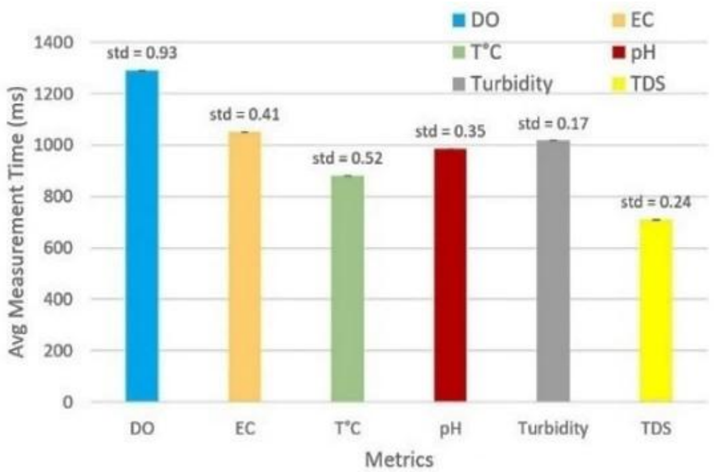


Figure 14. Sensor timing measurements

In this study, it was found that all the population densities of lettuce and tilapia, temperature, pH, DO, EC, and TDS, are fundamental basic metrics to evaluate water quality and that they remained within the recommended range. It was evident that the average temperature of the aquaponic system remained relatively constant, ranging between 26 °C to 29 °C, coinciding with the optimal parameters. Indicated the stability of the environmental conditions of the system and the suitability for successful cultivation [6].

During the procedure, the pH range in the tanks was maintained in a range of 6.5 to 8, which underlines the favorable conditions for the well-being and development of the fish in the aquaponic system [31]. To control turbidity, the system was configured to maintain a value between 15 NTU and 22 NTU. Coincident with the study carried out by Amri *et al.* [32], which assured that crops would be affected by the availability of light and would affect the ability of fish to feed adequately. In the aquaponics system, specific ranges for EC and TDS were established, to monitor the total ionic content of the water, the amount of inorganic salt, and dissolved organic matter. The set values were 1,000-1,500 µS/cm for EC and 900 ppm to 1,200 ppm for TDS, which is recommended to keep EC below 5,000 uS/cm and TDS below 2,500 mg/L [33]. Dissolved oxygen (DO) plays a critical role in nitrification, directly affecting bacterial activity that converts ammonium to nitrite and then nitrate. This correlation varies depending on water temperature: at higher temperatures, water tends to retain less oxygen, which can impair the effectiveness of nitrification. During the tests, ranges of values in the DO range between 5 and 8.5 mg/L were observed, which was slightly higher than the range recommended by Al Tawaha *et al.* [34], which suggests maintaining the DO between 4.0 mg/L and 6.0 mg/L. However, Medrano *et al.* [17] used a level higher than 4.5 and went up to 8.0, obtaining good results in the growth of the crops. If the parameters are not adjusted to the pre-established ranges, this would indicate that the water is contaminated and would cause reduced growth or death of the crops. Control systems in aquaponic environments need to be designed in a way that can adjust parameter values quickly, to minimize any negative effects it may have on the growth of both fish and plants [15].

The implementation of the IoT system shows that the survival rate in the first 4 weeks was 97.5%, which is higher than that presented by Aisyah [27] who obtained 82%. Regarding the SGR, the results obtained in this study showed a value of 4.89%±0.17% with a population of 40 fish, which is higher than that obtained in the research carried out by [35]. In that study, specific growth rates of approximately 3.68%±0.17% and 3.44%±0.22% were reported for populations of 30 and 40 tilapia respectively, suggesting a significant improvement in growth compared to previous findings. This difference could be attributed to the lack of control of the parameters of turbidity and electrical conductivity, fundamental aspects to evaluate water quality. Regarding the FCR, the automated aquaponic system reached a value of 1.53±0.09, which indicates greater efficiency in food conversion compared to the study carried out by [36]. In that study, FCR values of 1.69 and 1.80 were reported for Nile tilapia production in an aquaponic system, suggesting improved feed conversion performance in our automated system. These values are similar to those obtained in the present study, which is an encouraging indicator. In the case of the FCR, it is important to highlight that the recommended range for culture of red tilapia fingerlings is between 1.0 and 2.4. With the system, it has been successfully achieved to maintain the variables at the appropriate parameters, which reflects effective management in feed conversion and contributes to the overall success of growing red tilapia in the aquaponic system.

4. CONCLUSION

The pH sensor has a lower precision rate than the other sensors since it has a coefficient of variation (CV) of 7.24, a relative error of 4.55, and a standard deviation of 0.82. On the contrary, the turbidity sensor has a better precision rate, because it has a CV of 1.61, a relative error of 2.25, and a standard deviation of 0.73. Therefore, the sensing system, despite these variations in its results, proves to be accurate when detecting the water quality parameters.

When using the TDS sensor through the IoT to send information from the application (APP), the times ranged from 0.68 to 1.27 seconds. The TDS sensor was the most suitable for an aquaponic system, as it allows information to reach the user in almost real time. On the other hand, the DO sensor turns out to be the least efficient because it takes a while to send the information.

The average complete detection period is approximately 0.97 s, even when there are seven sensors in operation and the user is away from the facility. This allows the device to automatically control water quality conditions by operating the base liquid and pH supply pump, mini water pump, water recirculation pump, air pump and Peltier elements with rapid response. This regulates the parameters and brings them to the optimal range for crop growth.

The automated aquaponic system proved to be suitable for tilapia cultivation because it controlled the parameters in real time. During this period, tilapia exhibited a remarkable ability to adapt to different environmental conditions, having high resistance and high productivity. Furthermore, a significant improvement could be observed in the SGR, where the highest values were 6.21±0.24%, compared to the initial values which were 4.89±0.17%.

The reflux aquaponic system was found to be highly effective for tilapia cultivation, evidenced by the notable increase in growth performance. Significant improvements were obtained in the results, as reflected in the SGR, which went from 4.89%±0.17% to 6.21%±0.24% with the implementation of the system. Likewise, a notable reduction in FCR was recorded, which decreased from 1.98±0.14 to 1.53±0.09 when the aquaponic system was installed. This would indicate that the nutrients and food supplied to the fish are being used more efficiently because the survival rate of tilapia increased from 85% to 97.5% after the implementation of the aquaponic system.

On the other hand, lettuce growth also experienced significant improvements. Notable differences were observed in the height, number of leaves, leaf length and weight of the plants, before and after the control system, with increments of 7.74 cm, 5 leaves, 5.6 cm and 41.6 g respectively. These differences were more significant as the weeks passed after the day the control system was installed.

The aquaponic system proposed in this research offers multiple benefits. By taking advantage of cloud storage and creating a database for the system, you contribute to management decision-making. Allowing you to maximize the efficiency of growth inputs and preserve fundamental resources such as water and nutrients in the long term.

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