Design of an Automated Irrigation and Lighting System for a Two-Tier Nutrient Film Technique Hydroponics

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Abstract

Precision agriculture strives to provide the needs of plants so they can grow with excellent health and yield. Light and nutrients are major parameters that affect plant growth. Several research on hydroponics focus on either the lighting system or the nutrient system but do not consider the correlation of both light and nutrients to plant development. In this research, a design of an automated fertigation system that monitors the photoperiod and nutrient consumption based on a Proportional-Integral-Derivative (PID) system was observed. The PID system was used to control the conductivity and acidity of the solution by opening a solenoid valve which adds nutrients, base, acid, or water to the reservoir of the hydroponics system. The light system was controlled to run the photoperiod needed by the plant. Nutrient consumption was measured based on the electrical conductivity at the start and end of the hydroponics system. The results of the design showed that the light was set at a 16-hour photoperiod and the PID system maintained the nutrient parameters within the recommended levels with several reading deviations that were caused by the accumulation of residue, lack of air circulation, lack of water agitation, and water leveling. The plants were managed for efficient growth by monitoring parameters in the hydroponic system where stabilized nutrient consumption was observed at 0.4S/m to 0.6S/m.

***Keywords* — Fertigation system, Hydroponics, Photoperiod, PID, Precision agriculture**

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I. Introduction

Traditional farming is soil-dependent agriculture that encounters water scarcity, low production rates, and unsustainable eco-friendly practices [1]. The viable solution for the concerns as mentioned above is the development of alternative farming techniques such as smart irrigation control systems that improve the water consumption and labor demand of plants [2]. To strengthen the advantages of a greenhouse environment, soilless cultural system (SCS), such as hydroponic, aeroponic, and aquaponic systems were commonly used [3].

Hydroponics is a cultivation technique for plants to use water that may or may not have aggregates that provide nutrients to crops [4]. Previous studies demonstrated that the hydroponic culture technique generates favorable results compared to conventional farming practices [1] and has gained popularity from its wide range of benefits [5]. This method was observed to produce greater yield at a short maturation period yet have as much nutritional value as conventional farming. It also minimizes water and carbon footprint [6]. Other studies have also combined hydroponics with aquaculture to recycle nutrients from fish wastes [7]. Many hydroponics systems measure parameters such as pH and electric conductivity of the water solution and set these parameters to a standard range of values. Other parameters such as humidity, air and water temperature, light quality, dissolved oxygen, etc. are also important in maintaining a fast and healthy plant growth [8]. A study focused on monitoring the pH and conductivity levels of the nutrient solution and concluded that the two nutrient parameters correlate with plant growth [5]. Some studies focused on using an Arduino Uno microcontroller, which controls the flow of water to directly send the nutrients to the hydroponic roots at any given time [10] [11]. Aquaphotomics was also applied in a different study and discussed light-water interaction for detecting nutrient absorption [12].

The Nutrient Film Technique is a hydroponic system wherein nutrient solution is circulated using a water pump and gravity guides the water back to the reservoir [9]. The plant roots in this system develop through the shallow nutrient solution and the portion of the roots not submerged allows sufficient oxygen flow [10].

In various research, advanced technologies such as artificial intelligence control algorithms were implemented to analyze and control the nutrients supplied to NFT systems [10]. Existing research on hydroponics systems used a Proportional-Integral-Derivative (PID) controller to maintain nutrient solution distribution. PIDs are said to be cheap, simple, easy to implement, and provide robust performance for process control of a closed-loop system [13]. PID provides smooth control action and makes the system highly stable [14]. One research study used a PICI8F4550 microcontroller to implement a PID and performed Equation 1, which was approximated by Equation 2, to regulate electrical conductivity. The differential equations use the variables Kp, the proportional gain, Tm, the sampling time, Ti, the integration time, Td the derivative time and e(k) which is the error at time k. The difference between the desired EC value and the actual EC value is used to obtain the error e(k) [13].

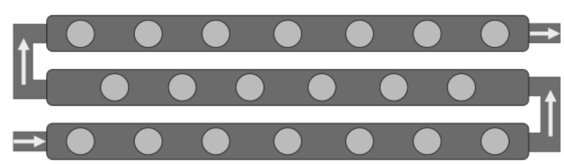
$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(t)dt + T_d e(t) \right] \tag{1}$$

$$u(k) = K_p \left[e(k) + \frac{1}{T_i} \sum_{j=0}^{j=k} e(j) \frac{T_m}{T_i} + \left(e(k) - e(k-1) \right) \frac{T_d}{T_m} \right] \tag{2}$$

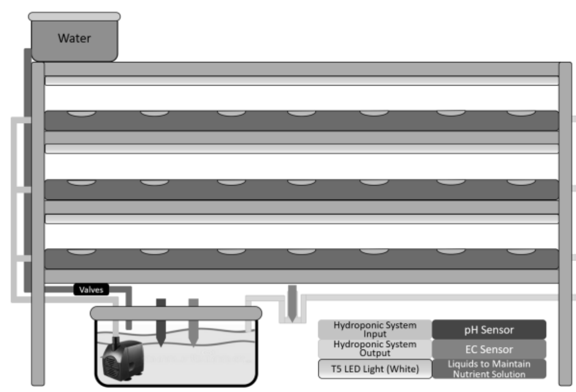
Light and nutrients are two major parameter groups in plant growth and development. Many hydroponics automated monitoring systems have only been applied to either nutrient or light parameters but not both. In this research, an NFT hydroponics system that considers the photoperiod and nutrient consumption of the plant was observed. The main objective of the study is to design an automated hydroponics system that manages the nutrient solution, provides periodic lighting, and monitors the parameters that affect plant growth which include nutrient consumption, acidity, and electrical conductivity of the solution, solution temperature, and humidity. The time spent for the liquid to circulate the fertigation system was measured and used as an offset in the computations of the PID system. The PID system was manually tuned using LabView and implemented in Arduino to control the electrical conductivity, acidity, and water level in the main supply tank to the specified ranges needed by the plant. The results of the PID system were observed based on the output of the sensors. An analysis of the outputs was made to evaluate the accuracy of the PID system to maintain the nutrient and light parameters.

II. System Architecture

Figure 1 shows the architecture of the system. It was composed of three layers of pipes in series, whereas each layer had 20 holes. Two liquid reservoirs were used in the system where the first one was filled with water to balance the acidity needed by the plant, and the other as the main tank, where the pH, nutrients, and water are mixed. Two pumps were placed in the main tank. One pump transferred the solution to the hydroponics system while the other pump was used for water agitation. Sensors monitored the temperature, pH level, and electric conductivity of the nutrient solution.



(a)



(b)

Fig. 1. Top view of pipes (a) and Front view of automated NFT hydroponics system (b)

A. Microcontroller

The microcontroller board used for the design of the system was the Arduino Mega based on the ATmega2560. It has 54 digital input/output pins and 16 analog inputs that can satisfy the number of connections needed by the sensors.

B. Sensors

The sensors used were the electrical conductivity sensor, the pH sensor, and the humidity and room temperature sensor.

The electrical conductivity sensor used for the hydroponics system was the DFRobot Gravity: analog electrical conductivity meter V2. It is an Arduino compatible sensor that measures the electrical conductivity of aqueous solutions. A temperature sensor was used to support the measurement accuracy of the electrical conductivity sensor and achieve automatic temperature compensation. Two electric conductivity sensors were used for measuring the nutrient consumption of the plants. The electrical conductivity sensor has a laboratory-grade probe with a measurement accuracy of ±5% F.S.

The pH sensor used was the DFRobot Gravity: Analog pH meter V2. It is a sensor compatible with Arduino, and it is designed to reflect the acidity or alkalinity of a solution. The pH sensor has a laboratory-grade probe with a measurement accuracy of ±0.1 at 25°C.

The DHT11 Temperature and Humidity sensor was used to measure the humidity and temperature of the greenhouse in the hydroponics system. A capacitor with 100nF was added to the circuit of the sensor for power filtering. The DHT11 sensor has a humidity range of 20 to 90% RH, and its humidity accuracy is ± 5% RH. Its temperature range is 0 to 50°C ± 2°C and its temperature accuracy is ± 2°C.

C. Grounding Isolation

The sensors of the hydroponics system were connected to a relay for electric isolation. The connection of the sensors to the relay is shown in Figure 2. Grounding isolation was implemented using two relays for the three sensors to resolve the inaccurate measurement of the sensors due to interference caused by the other sensors.

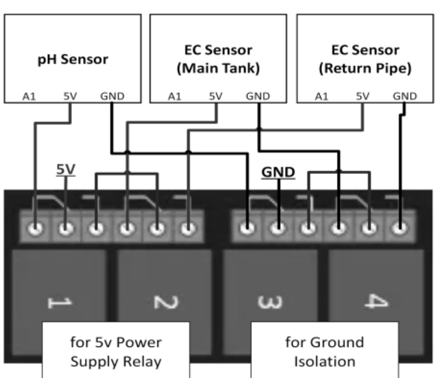


Fig. 2. Relay Connection for Electric Isolation of pH and EC Sensors

D. Electric Solenoid Valves

Electric solenoid valves control the input of nutrient solution, water, pH solution up solution, and pH down entering the main tank. The valves were controlled by the Arduino program based on the PID system. The electric solenoid valves used required a supply voltage of 12V. The valves were normally closed and has a pressure at the range of 0 to 0.8MPa.

The base, acid, water, and nutrient solution were supplied by individual electronic solenoid valves that were controlled automatically using the Arduino microcontroller, which opens the valve to distribute the needed amount of liquid into the main tank. The top view of the main tank and the connections for the flow of the nutrient parameters are shown in Figure 3.

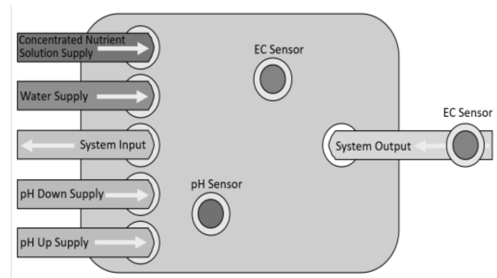


Fig. 3. Top View of The Main Tank with 4 Valves (from top to bottom): Nutrient Solution, Water, Acid, and Base

Two EC sensors were used to measure the electrical conductivity of the plant. The first EC sensor was positioned inside the main reservoir to measure the amount of the EC of the solution before the nutrient intake of the plant takes place. The same reading was used as an input to the applied PID equation in the Arduino code that maintains the EC value of the main tank. Another EC sensor was positioned at the end of the channel to record the electrical conductivity after the nutrient intake. The difference between the two EC sensors indicated the nutrient consumption of the plant. The temperature can influence the acidity and conductivity of the solution [5]. Temperature and pH sensors were used for the system to monitor the temperature and acidity of the nutrient solution, respectively.

E. LED

Plants need sufficient lighting for photosynthesis. Commercial greenhouses use light-emitting diodes (LED) to replace traditional lighting sources [3]. The lights used for the hydroponics system was the Philips Essential Smart 32Bright Light LED T8 Integrated BN016C with an initial luminous flux of 800 lm. LED lights are also more energy-efficient and cooler in temperature than fluorescent lights which are commonly used in hydroponics. The lights were turned on and off based on the photoperiod needed by the plant. A common practice in hydroponics culture is to use a 16-hour photoperiod [15].

Fig. 4. Light and Piping Design used in the Final Hydroponics System

F. Parameters of Crop

The design will focus on Romaine Lettuce as the plant of the system and the reservoir parameters is set to those listed on Table 1.

Table 1
Parameters for Lettuce Growth [4]

Parameter	Ideal Range
Daylight color temperature	5600K - 6500K
Ambient Temperature	21°C - 24°C
Relative Humidity	50% - 80%
pH Level	5.5 - 6.5
Electrical Conductivity	0.8 S/m – 1.2 S/m
Total Dissolved Solids	m – 840 ppm

III. Methodology

A. Cycle Duration

After the system set up was built, the time taken for the nutrient solution to circulate from the reservoir through the hydroponics system and back to the main tank was measured using EC sensors. The measured time was approximately 15 minutes, and this used as the offset for the measurement of nutrient consumption. This ensures that the measured solution in terms of EC that entered the system was the same batch of nutrient solution that was measured at the return pipe going to the main tank. The EC reading at the return pipe was expected to be lesser or similar than the EC reading in the main tank 15 mins earlier to signify if nutrient consumption took place or not.

B. PID System

PID controllers were implemented to the system to act as a feedback. The PID was responsible for adjusting the electrical conductivity and pH level of the nutrient solution by controlling the electric solenoid valves [13]. The pH and EC sensors in the main tank provided data to the PID and the PID adjusted the pH and EC level based on the range given in Table 1.

1. PID System in LabView

The PID controller is an algorithm that sets the behavior of the system using the feedback error as a control input. PID stands for Proportional, Integral, Derivative which will each provide a certain effect to the system. The gains Kp, Kd and Ki are inputs to control the PID and produce a desired output [16]. A PID control design was made using LabView to formulate a plant equation with gain values used to normalize the EC and pH level at the main nutrient reservoir of the hydroponics system. The block diagram of the PID control design is shown in Figure 5.

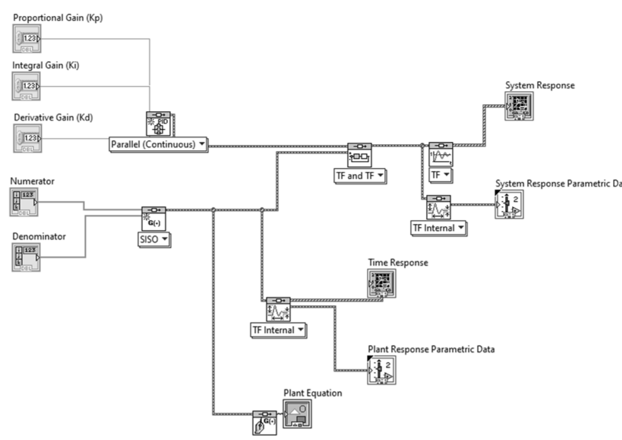


Fig. 5 – Block Diagram of PID Control Design using LabView

Manual tuning was applied based on the individual effects of P, I and D as stated in Table 2 [17]. The system gains were set to produce the desired output of the system response.

TABLE 2
EFFECTS OF INCREASING PID PARAMETERS INDEPENDENTLY [17]

Response	Increase in K_p	Increase in K_i	Increase in K_d
Steady-State Error	Decrease	Eliminate	Minor Change
Rise Time	Decrease	Small Decrease	Minor Change
Overshoot	Increase	Increase	Decrease
Settling Time	Minor Change	Increase	Decrease
Stability	Degrade	Degrade	Improve

The proportional gain (Kp) was set to 50 and this determined the ratio of the output response to the error signal and produced a proportional linear reaction to the error. The integral gain (Ki) was set to 15 and this drove the steady-state error to gradually become zero. The differential gain (Kd) was set to 2,000 and this caused the output to decrease if the process increases rapidly. Given the stated gain values, the plant equation and plant response were derived. The system response produced an oscillating output as shown in Figure 7. This response gradually brought the output of the system to a zero value and maintained the parameters that should be normalized in the system.

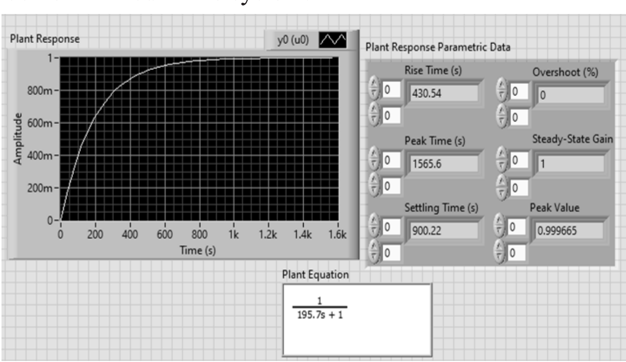


Fig. 6. Plant Response and Plant Equation of PID Control Design in LabView

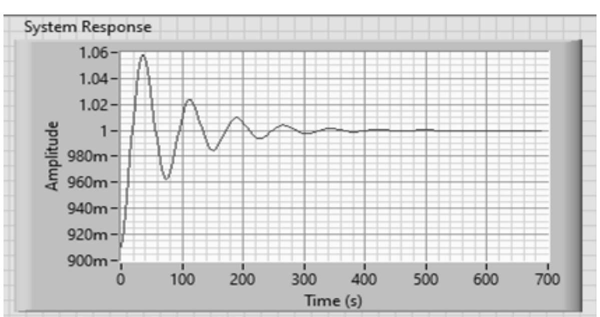


Fig. 7. System Response of PID Control Design in LabView

Digital Implementation of PID Controller

The theoretical model of the analog PID controller in parallel form was shown in Equation 3 where, Y(t) is the controller variable, e(t) is the error signal, Kp is the proportional gain, Ki is the integral gain, and Kd is the derivative gain. This equation was used to derive a discrete PID equation for a digital implementation of the PID controller. The Z-transform of the theoretical equation was converted to the discrete domain for the nth sample and further simplified to produce Equation 4 where variables K1, K2 and K3 are simplified forms of Equation 5, 6 and 7. Testing and implementation became more flexible with the digital implementation [18].

$$Y(t) = K_p * e(t) + K_i * \int_0^{\tau} e(t)dt + K_d * \frac{de(t)}{dt}] \quad (3)$$

$$Y(n) = Y(n-1) + K1 * e(n) + K2 * e(n-1) + K3 * e(n-2) \quad (4)$$

where

$$K1 = K_p + K_i + K_d \quad (5)$$

$$K2 = -K_p + 2K_d \quad (6)$$

$$K3 = K_d \quad (7)$$

C. *Flow of Feedback System*

The acidity level of the nutrient solution was measured every 20 milliseconds. The average of the pH reading was taken every minute followed by the readings of the EC sensor in the main tank, and then the EC sensor in the return pipe. The nutrient solution temperature assisted the reading of the EC sensors [5]. The room temperature and humidity were also taken per minute. Every 12 hours, when the EC reading in the main tank is less than 1000 µS/m or the recorded acidity is greater than 6, the recent recorded EC reading and recorded pH average in the main tank became the inputs of the PID equations for maintaining the EC and pH level, respectively. The PID produced an output of DC signals that controlled the relay of the electronic valves. These signals correspond to the duration of which the valves open. The valves supplying the water, or the concentrated nutrient solution operated first for the maintenance of EC level. After which, the valves for the pH up solution or pH down solution operated for the maintenance of the pH level. Then, the valve of the water supply opened until the desired water level was attained as monitored through a water level sensor. The duration that the lights turned on or off was controlled through a relay, giving a 16-hour photoperiod to the plant or any duration desired. The EC conductivity readings in the main tank were subtracted with the 15 minutes later EC reading at the return pipe, the NFT system output that brings the liquid back to the main tank, to get the nutrient consumption of the plant.

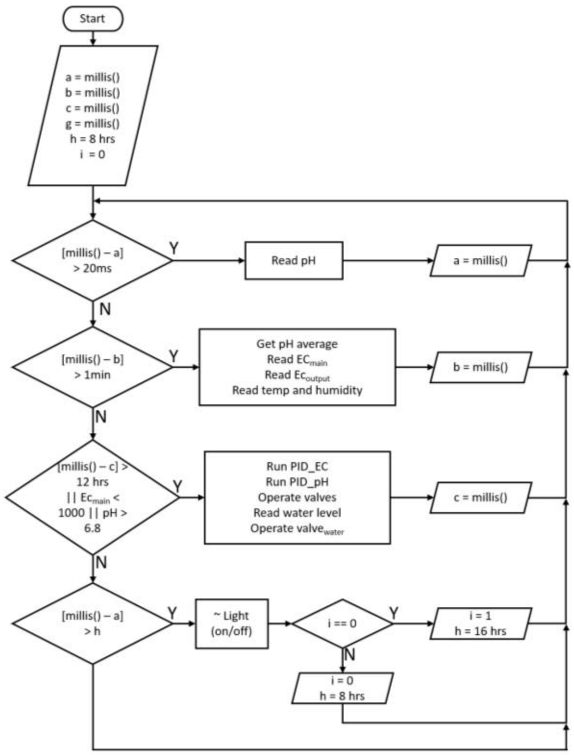


Fig. 8. Flowchart for the Feedback System for the Nutrient Parameter

V. Results

The reading for the EC sensor in the main tank (Blue) and EC sensor in the return pipe (orange) is shown in Figure 9. The first blue spike indicates that the nutrient solution was added to the main tank, and its value decreased when the solution circulated the system. The orange waveform rose at 500 seconds as the nutrient solution slowly flows through the system and into the return pipe. In approximately 900 seconds, the waveforms have equalized. This states that the nutrient solution completed a cycle through the pipes. Thus, the measured time for the nutrient solution to circulate from the main tank and through the system is approximately 15 minutes (900 seconds). The duration of the cycle of the solution was used as an offset time to measure the nutrient intake of the plant in terms of EC and the settling time for the PID.

A total of 40 seedlings of romaine lettuce were transferred from the nursery to the hydroponics system after the EC and pH maintained at their specified level. Data was monitored and gathered for less than 12 days.

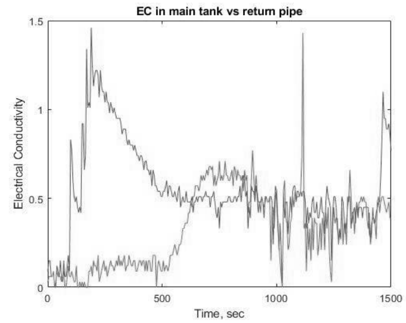


Fig. 9. Graph of EC in Main Tank [Blue] Versus EC in Return Pipe [Orange] to measure cycle duration of the solution

Figure 10 shows two waveforms, the EC levels from the main tank (orange) and EC levels from the return pipe (blue). At time = 0, the EC started around 1.1S/m. The graph shows that the EC in the main tank (orange) fluctuated between 1.1S/m to 1.4S/m which exceeded that specified value of 0.8S/m to 1.2S/m set in the PID. Accumulation of residues inside the main tank and pipes due to lack of agitation may have caused the EC readings to exceed 1.2 S/m. The increase in EC in the main tank was also a result of the water consumption of the plant that leads to lesser water in the tank due to a hot environment [19]. The EC in the return pipe slowly declines from time = 0hr up to time = 40hrs as the plant absorbed the nutrients from the solution. A water level sensor was not yet implemented at this time. Water was manually added into the tank since the water evaporated from the pipes and tank reducing the water level inside the system. Adding water decreased the EC in the tank towards the specified range. The EC solution at the return pipe at time = 110hrs suddenly increased from 0.7S/m to 1.3S/m. This indicated that there was no nutrient consumption. The decrease of EC reading at the return pipe approaching time = 200hrs signified that the plant was consuming nutrients again.

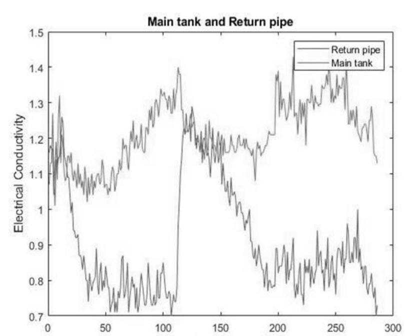


Fig. 10. Graph of EC in Main Tank (Orange) and EC in Return Pipe (Blue) to observe PID Performance

The difference between the reading of the EC in the main tank and the EC reading at the return pipe reflects the nutrient consumption of the plants. In Figure 11, the plant did not consume nutrients when the y-axis is equal to 0 and it consumed nutrients when the y-axis is above 0. At time = 0, the consumption slowly rises at a steady pace. At time = 110hrs, the difference suddenly dipped and slowly rose due to the manual addition of water in the system to compensate for the solution level in the system. After the solution level manual compensation, the consumption stabilizes again around 0.4S/m to 0.6S/m.

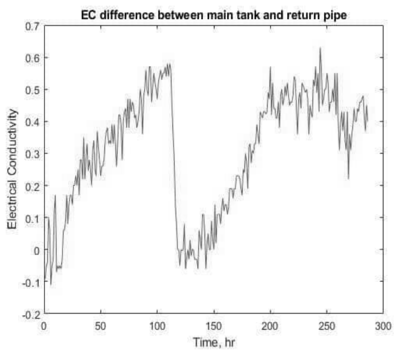
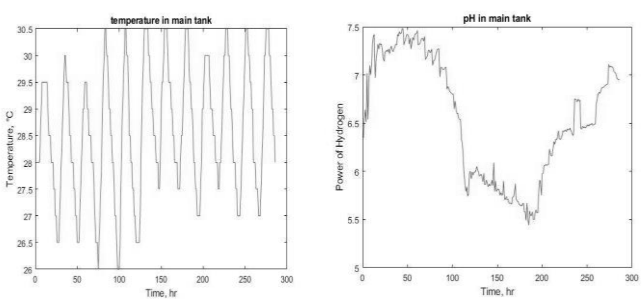


Fig. 11. Nutrient Consumption of Plants in the Hydroponics System

The temperature of the solution fluctuates due to the heat in daylight compared to nighttime. The temperature peaks at 30.5 Celsius and 26 Celsius at minimum as shown in Figure 12a.



(a) (b)

Fig. 12. Graph of (a) Temperature and (b) pH level in the Main Tank

The acidity levels in the time = 0 to time = 100hrs exceeded the recommended acidity levels of the plant due to the accumulated solution inside the main tank. In the hot environment, some water evaporated, and the plant absorbed more water causing residues and imbalance to the nutrient solution pH levels in the tank. After some time, water was added, and the acidity levels reached the recommended range of 5.5pH to 6.5pH.

V. Conclusion

The design of an automated hydroponics system in this research focused on monitoring and managing the nutrient solution parameters using a PID system while providing periodic lighting to the plant. The lights were set to a 16-hour photoperiod. The T8 8W LED lights were placed a foot above the pipes which produced the leggy growth of the lettuces. This shows that the light intensity on the leaf canopy regions was insufficient. The measured time for the liquid to complete a cycle in the hydroponics system was approximately 15 minutes (900 seconds). This cycle duration was used as the settling time for the PID and the offset time to measure nutrient intake of the plant. The PID was programmed to maintain an EC level between 0.8 S/m and 1.2 S/m but the graph displayed readings between 1.1S/m to 1.4S/m. This might be due to residues forming in the tank and pipes adding up to the total EC of the solution and the decrease of water level in the tank because of the plant's water consumption as a result from a hot environment. Nutrient consumption per cycle was measured based on EC levels in the main tank and the return pipe and was observed to stabilize at approximately 0.4S/m to 0.6S/m. Measured temperature of the solution reaches minimum of 24 Celsius and a maximum of 30.5 Celsius which exceeded the recommended temperature for growing lettuce. Adding air circulation inside the greenhouse can lower the ambient temperature. Stable pH levels are within the range of 5.5pH and 6.5pH but accumulation of solution in the tank will cause pH level to exceed recommended acidity levels. The performance of the PID was not fully observed since automated water leveling was not implemented. This caused the EC and pH readings to go beyond the desired levels. Control of nutrient solution concentration in the system can be improved by implementing water leveling.

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