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IoT-enhanced mechanical system for fogponic cultivation: air circulation and environmental control

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Abstract

Fogponic cultivation, a hydroponic technique that utilizes water mist for nutrient delivery, offers a significant advantage in water and nutrient efficiency. However, suboptimal air circulation, temperature, and humidity in the root chamber can hinder plant growth and nutrient uptake. This study develops an IoT-enhanced mechanical system to optimize environmental conditions in a fogponic root chamber for cultivating spinach (Spinacia oleracea) seedlings. An actuator in the form of a fan was integrated to regulate air circulation, and managed by a Proportional Integral Derivative (PID) controller for precise temperature and humidity control. The system was monitored using the IoT-based Blink application. The results showed that the PID controller effectively regulated environmental conditions, with optimized parameter values: Kp = 5.76, Ki = 0.576, and Kd =14.4. Performance comparisons with P, PI, and PD controllers demonstrated effective humidity control, achieving the target set point of 92% with rise times of 447–1090 seconds and steady-state errors of 0–0.5%. By integrating mechanical components such as the fan with IoT-based monitoring, the system achieves continuous adjustments to the environment, enhancing plant growth conditions.

Keywords: IoT, fogponic, mechanical, monitored, PID

1 Introduction

Green spinach is a vegetable that is often consumed by the wider community. Green spinach has a high nutritional content so it is in great demand [1]. Green spinach is a vegetable rich in vitamins, protein, carbohydrates, fat, iron, and fiber. The increase in businesses that use green spinach raw materials and public awareness about healthy living is increasing so the demand for spinach continues to increase [2]. However, conventional cultivation of spinach plants causes the nutrients obtained by spinach to be uneven because in conventional cultivation techniques, spinach seeds are spread without regard to distance so there is competition for nutrients in plants that are so close together [3]. Households are increasingly interested in learning about hydroponic systems for growing spinach. This system is attractive because it can be used in small spaces and multi-storey houses. In addition, the system can also be used in closed houses with the help of artificial light. To guarantee the growth and development of the plants, nutrients should be checked regularly [4]. Hydroponics provides the plants' needs for water, nutrients, and oxygen through controlled irrigation. In hydroponics, there are many nutrient delivery systems, including water culture, wick, tidal, NFT, drip system, aeroponics, and fogponics [5] [6].

Fogponics is a more sophisticated and efficient method of plant cultivation than aeroponics [7]. Similar to aeroponics, the fogponics method uses water vapor to provide nutrients to the roots of plants suspended in the air, while in the aeroponics method, the provision of nutrients is done by spraying nutrient solutions to the roots of plants [8]. Fogponic cultivation provides many advantages such as minimizing the use of water and nutrients by up to 50% due to the limited use of water. In addition, the rich nutrients carried by the water mist penetrate the plant roots so that the plant roots are moist and well-nourished [9].

The nutrient water mist in fogponic cultivation is generated by an ultrasonic mist generator placed in the nutrient solution container. For the growing media, rockwool, fiber, and hydroton are used [10]. The roots of fogponic plants must always be given a mist of nutrient solution so that they do not dry out and wither. The intensity of the mist must also be adjusted so that it is not too low or too high so that the roots can breathe and absorb nutrients optimally [3]. Inappropriate temperature and humidity can affect the growth of fogponik plants. If the temperature is too high, the nutrient solution will evaporate, causing the plants to lack nutrients. If the temperature is too low, the absorption capacity of the plant roots will be reduced. If the humidity is too high, evaporation and absorption of plant roots will be reduced. If the humidity is too low, the plant may develop a shoot scorch at the edge of the leaves. Temperatures exceeding 30ºC or below 4ºC are likely to cause abnormalities in the plant and the worst possibility is that the plant will die and be attacked by disease. As for the humidity value, it should be higher than 80% of the mist production resulting from the nutrient solution for the plant roots [11]. While spinach needs plenty of sunlight, a temperature of 30 degrees Celsius and humidity of more than 80% is considered the ideal humidity temperature for spinach growth [12] [13].

This research develops previous research with the title Energy efficient smart indoor fogponics farming system [14] [15]. This research produced a fogponic prototype that regulates the fogging of the nutrient solution for lettuce cultivation. However, it has a drawback: the ultrasonic fogger operates on a fixed schedule, causing the temperature and humidity levels to deviate from the ideal conditions of a cold fogponing root chamber [16]. There is also research conducted by John Newton et al (2024), this research focuses on the position of the Ultrasonic Fogger, but the Ultrasonic Fogger which works continuously causes the temperature to rise beyond 30ºC, and the absence of air circulation in the root space of the plant results in malnutrition in the plant.

Therefore, based on the shortcomings of previous research, a fan will be implemented to circulate air and control and monitor humidity and temperature in the fogponic root chamber [17]. Thus, the temperature and humidity conditions in the fogponic root chamber are in accordance with the conditions needed for plants to grow according to the setpoint. The tests of this research are as follows:

1. A fan is implemented to circulate air and control the fan speed so that the distribution of nutrients to plants is even.
2. Design a PID-based control system to maintain the stability of the temperature and humidity of the fogponic root chamber. In PID control, the Ziegler-Nichols method is used [3].

To maintain stable temperature and humidity in the fogponic root room, we designed a PID-based control system. The PID control utilizes the Ziegler-Nichols method [3]. Designed an IoT-based monitoring system that can monitor the temperature and humidity values of the fogponic root chamber via smartphone microorganisms [17] [18] root interactions with arbuscular mycorrhizal fungi, and root interactions with legume-rhizobia [19]. However, studies of spinach plant root temperature treatment are essential to improving spinach production using aeroponics. An optimized plant root environmental temperature can increase the root aeration and thus has the potential to improve plant production. Therefore, this study aimed to develop aeroponics root chamber temperature conditioning for mini-tuber potato seed cultivation.

2 Research method

2.1 Fogponic system

Fogponics is a soil-less plant cultivation method that uses water vapor to transport oxygen and nutrients to the plant roots. This technique is a development of aeroponics, which uses water sprays to transfer nutrients and oxygen [15] [18].

In Fig. 1, spinach (Spinacia oleracea) cultivation using the fogponics method is illustrated, where the nutrient solution is provided with the AB Mix nutrient formula. The planting media that can be used include rock wool, fiber, hydroton, and flannel. In fogponics, plant roots are suspended in a root chamber filled with a 5-30 μm mist, which is generated by an ultrasonic vaporizer. This vaporized nutrient solution enables nutrients and oxygen to be efficiently absorbed by the roots [17] [20] [21]. Fogponics offers several advantages over other crop cultivation methods, including high water use efficiency, reduced disease risk, and improved crop quality.

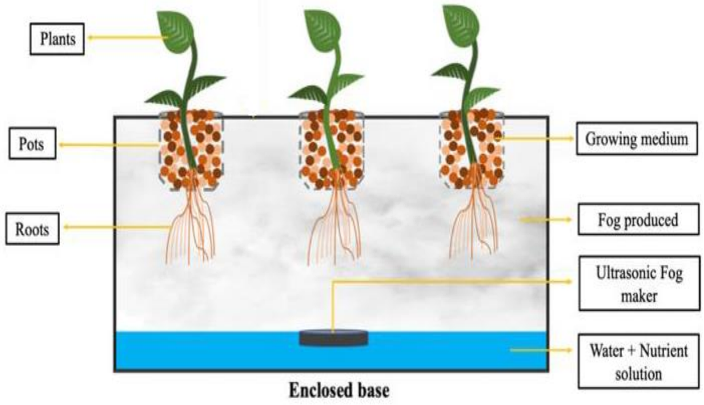


Fig. 1. Fogponic cultivation system [11].

2.2 Research Stages

The research stages were carried out with hardware design, software design, prototype testing, data collection, data presentation and concluding as described below: In plant cultivation using the fogponic method, the nutrient solution was provided with the AB Mix nutrient formula. Planting media that were used included rock wool, fiber, hydroton, and flannel. In fogponics, plant roots were suspended in a root chamber filled with 5-30 μm mist. This mist was produced by an ultrasonic vaporizer. The nutrient solution was vaporized at the roots by the ultrasonic vaporizer, so that nutrients and oxygen could be absorbed by the roots [19]. Fogponics offered several advantages over other plant cultivation methods, including high water use efficiency, low disease risk, and better plant quality [10] [17] [22].

2.2.1 Hardware and software design

At the hardware design stage, a tool concept was designed in the form of a box that can regulate and maintain temperature and humidity by implementing a DHT22 sensor, 12V DC Fan, Mist Maker, 16x2 LCD, L982n Driver, and LM2596 Step-down Module. This tool used a NodeMcu microcontroller. The hardware design as shown in Fig. 2.

Fig. 2 shows the Wiring Diagram Hardware design for the fogponics plant cultivation system. This circuit uses the NodeMCU ESP8266 microcontroller which is connected to various components as follows:

1. NodeMCU ESP8266 microcontroller as the control center.
2. The Ground pin on the NodeMCU ESP8266 is connected to the Ground on the DHT22 component, 16x2 LCD, L298n Motor Driver, and 5V Relay using a black cable.
3. The Vin pin on the NodeMCU ESP8266 is connected to the VCC DHT22, LCD 16x2, Motor Driver L298n, and Relay 5V using a red cable.
4. Pin D1 on the NodeMCU ESP8266 is connected to the SCL LCD 16x2 with a yellow cable.
5. Pin D2 on the NodeMCU ESP8266 is connected to the SDA LCD 16x2 with an orange cable.
6. Pin D3 on the NodeMCU ESP8266 is connected to the ENB Motor Driver L298n with a brown cable.
7. Pin D4 on the NodeMCU ESP8266 is connected to Data DHT22 with a gray cable.
8. Pin D5 on the NodeMCU ESP8266 is connected to the NC Relay 5V with a purple cable.
9. Pin D7 on the NodeMCU ESP8266 is connected to IN3 Motor Driver L298n with a blue cable.

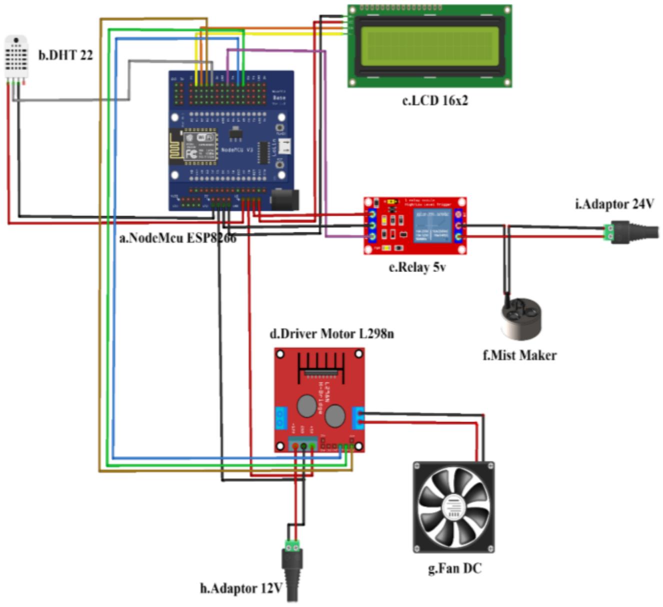


Fig. 2. Wiring Diagram Hardware Prototype

On the other hand, software design was carried out using C language supported by the NodeMcu microcontroller using the Arduino IDE application. The system block can be seen in Fig. 2 The PID used here uses Tunning Ziegler-Nichols.

2.2.2 Fogponic prototyping

After designing the hardware and software, a prototype is created based on the tool concept in the form of a box where sensor testing is carried out. Here we tested the system using PID control and the Blink application to see the growth of spinach using the fogponic method. The control system and the Blink application are used to monitor the growth of spinach using the fogponic method. The front view of the fogponic spinach growth prototype as shown in Fig. 3.

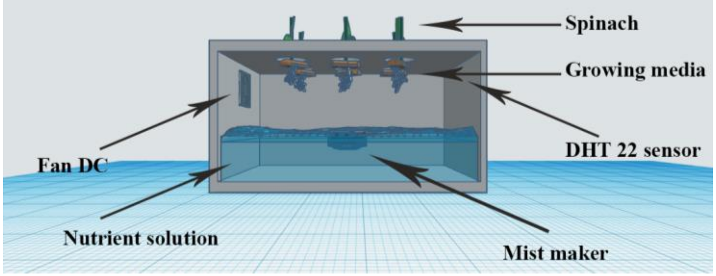


Fig. 3. Front view of the fogponic spinach growth prototype.

3. Results and discussion

3.1 Modeling with PID control

Ziegler-Nichols is one of the most popular PID controller parameter tuning techniques as shown in Fig. 4. This method begins by measuring the system's response to certain inputs and then uses guidelines to graph the system's response to establish two constants: the delay time (L) and the time constant (T). The Ziegler-Nichols method is proven to be effective in tuning PID controller parameters in stable systems. The optimal PID controller parameter values can be determined by knowing the values of these two constants. Here we use the Proportional (P), Integral (I), and Derivative (D) parameters to regulate the 12V DC fan speed so that the system remains stable at the setpoint value

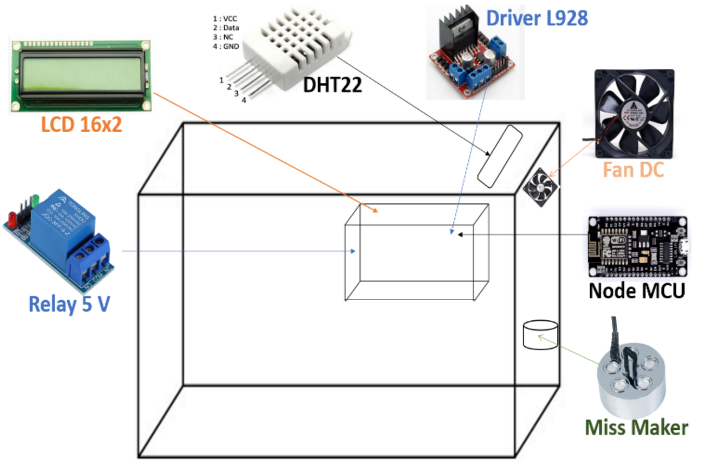


Fig. 4. PID Control Model Hardware

The Ziegler-Nichols open-loop method was chosen as the primary tuning approach due to its effectiveness in providing a well-balanced response between stability and performance. While the Cohen-Coon method is specifically designed for open-loop systems, it tends to be more aggressive and may introduce higher overshoot, which is less desirable in maintaining stable temperature and humidity conditions in the fogponic root chamber. Due to a lack of Integrators and derivative control, the plant has a shaped reaction curve letter S against the ladder input. The plant reaction curve calculates time constant T and time delay L. Fig. 4 then displays the serial plotter's reaction to DHT22 humidity readings via data variables DHT22 in Arduino program. According to the tuning rules The first Ziegler-Nichols method uses lines help to determine two constants, namely delay tim (L) and the time constant (T), the graph shows that the plant model has a process output (P) in the form of constantly increasing humidity up to reaches a steady state, such as that shown in the following Eq. (1)

$$\mathrm{Gc}(s) = 5.76 + \frac{0.576}{s} + 14.4s \tag{1}$$

The Kp, Ti, and Td parameters of the PID controller, as in Table 1, were obtained from the graphical data of the open-valve system response, following the Ziegler-Nichols parameter tuning rules in the first approximation.

Table 1. PID parameters on humidity control

Controller Type	K_p	T_i	T_d
P	$\frac{Tc}{L}$	∞	0
PI	$0.9\frac{Tc}{L}$	$\frac{Tc}{0.3}$	0
PID	$1.2\frac{Tc}{L}$	$2L$	$0.5L$

From Table 1, the proportional control value (Kp) was 4.8, the integral control value (Ki) was 0, and the differential control value (Kd) was 0. Using the tuning results, the T value of 24 and the L value of 5 were substituted into the Ziegler-Nichols rule, yielding results as in Eq. (2).

$$Kp = 0.9\,\frac{Tc}{L} \qquad Kp = 0.9\,\frac{24}{5} \qquad Kp = 4.32 \tag{2}$$

$$Ki = \frac{Tc}{0.3} \qquad Ki = 16.6$$

The results obtained for the proportional control value (Kp) were 4.32, the integral control value (Ki) was 16.6, and the differential control value (Kd) was 0. However, the test for the PD controller did not comply with the Ziegler-Nichols rules. Therefore, modifications were necessary, requiring the assignment of Kd = 0. Based on this, the system was modified by setting Kp = 5.76, Ki = 0, and Kd = 14.4.

3.2 Humidity control testing with controller PID

After obtaining the Kp, Ki, and Kd values, the next step is to integrate the PID controller into the program and upload it to the Arduino Uno. Several techniques were employed, including testing with the PID controller, testing with variable setpoints, testing with disturbances, and evaluating the resulting PWM output to control ultrasonic humidifiers and fans, to simulate the system response.

Fig. 5(a) illustrates the system response to a setpoint humidity of 92.5 % with the PID controller. Fig.5 shows a graph of the root chamber humidity response after the application of the PID controller for a period of 1800 seconds. In the graph of the humidity sensor results in the fogponic root chamber, it can be seen that the initial humidity in the root chamber was 84.10%. Furthermore, humidity reached the setpoint of 92%, with a rise time of 474 seconds, and stability reached 92.5% at 865 seconds. Within the framework of this research, the fastest rise time that can be achieved is 474 seconds. The rise time and stable state error values of the PID control system are then analyzed and obtained from Eq. (3). Humidity response of fogponic root chamber after applying PI controller for 1800 seconds as shown in Fig. 5(b).

Rise Time = 474 (3)
Steady State Error = $H_{steady} - H_{setpoint}$ = 92.5 – 92,0 = 0,5

Fig. 5(b) depicts the humidity response graph of the fogponic root chamber after applying the PI controller for 1800 seconds. In the visualization of the results of the humidity sensor readings in the root chamber, it can be seen that the initial humidity in the root chamber reached 88.10%. Furthermore, humidity reached the setpoint of 92%, with a rise time of 447 seconds, and stabilized at 92.30%. The rise time and stable state error values of the PID control system were then analyzed and from as Eq. (4).

Rise Time = 447
Steady State Error = $H_{steady} - H_{setpoint}$ = 92.3 – 92,0 = 0,3 (4)

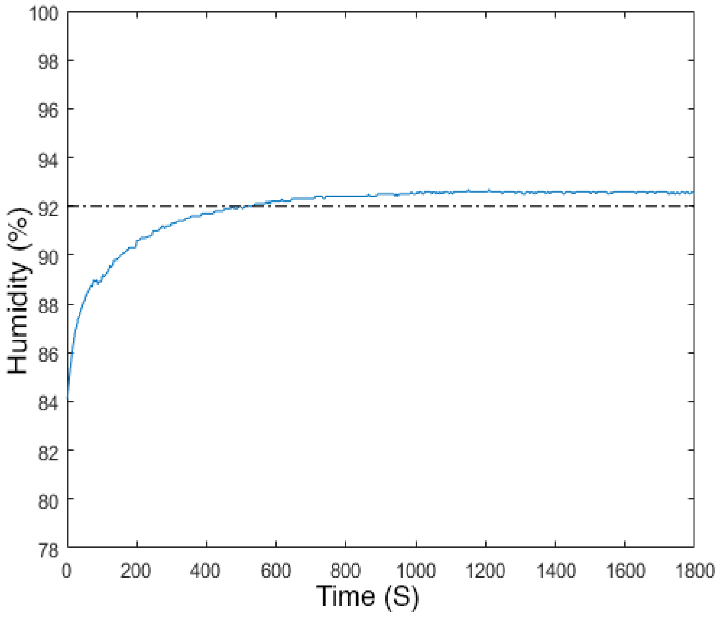
Fig. 5(c) illustrates the moisture response graph of the fogponic root chamber after applying the PD controller for 1800 seconds. In the representation of the humidity sensor reading results in the root chamber, it can be seen that the initial humidity in the root chamber reached 85.00%. Next, the humidity reached the setpoint of 92%, with a rise time of 914 seconds, and stabilized at 92%. Data regarding the rise time and stable state error values of the PID control system were then analyzed and obtained from Eq. (5).

Rise Time = 914
Steady State Error = $H_{steady} - H_{setpoint}$ = 92.0 – 92,0 = 0,0 (5)

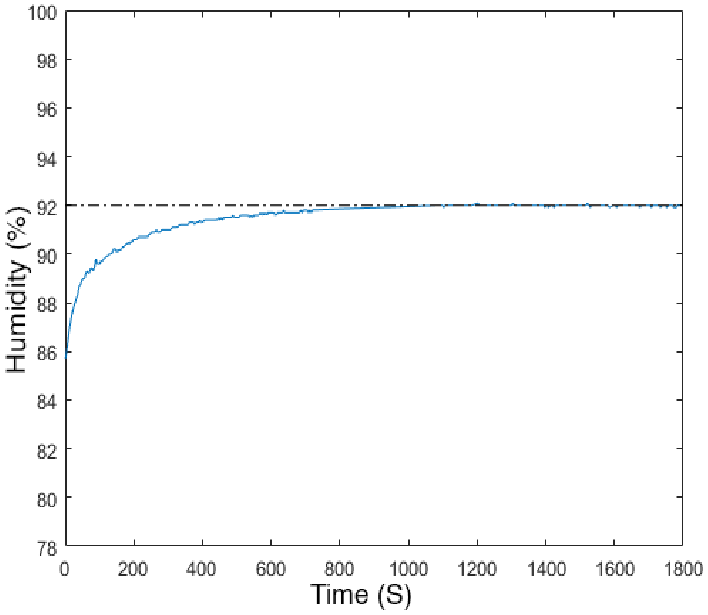
Each control system has rise time and stable state error characteristics, which are recorded and documented in the Table. 2. This data helps in understanding the comparison and evaluation of control system performance based on the approaches used, namely P, PI, PD, and PID.

Table 2. Comparison Result of P, PI, PD, and PID Control System

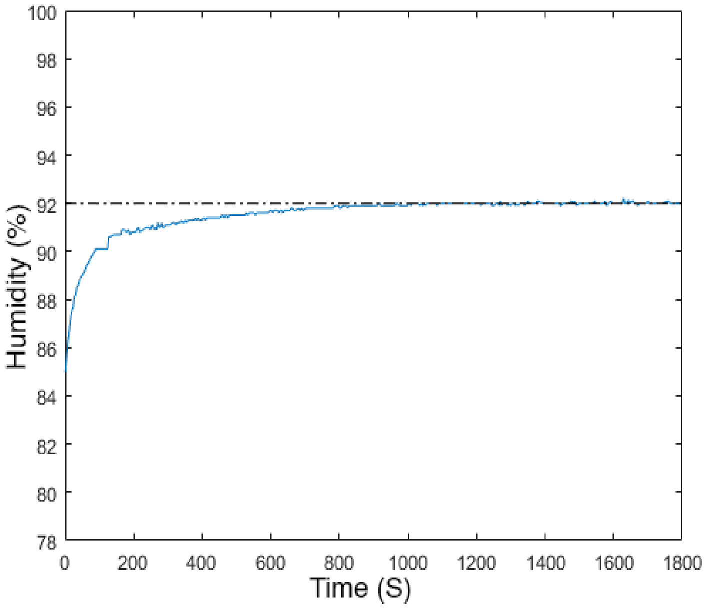
	Humidity (%)	Rise Time (Second)	Steady State Error (Integer)
SP	92	-	-
P	92	1090	0
PI	92,3	447	0,3
PD	92	914	0
PID	92,5	474	0,5



(a) PID



(b) PI

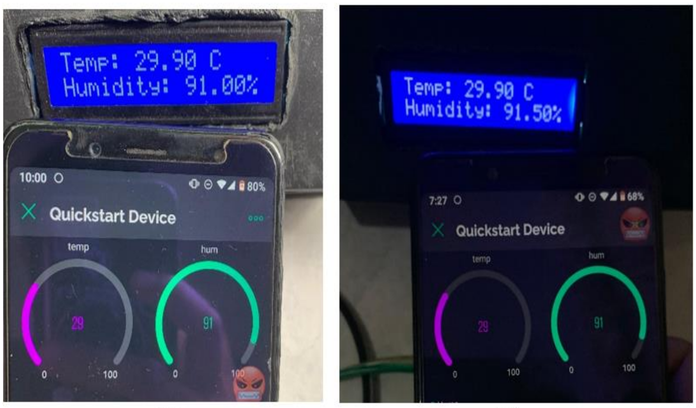


(c) PD

Fig. 5. Humidity graph of fogponics root room by different controller

3.3 Testing the Blynk monitoring system

The monitoring mechanism with Blynk involves several main steps: first, the NodeMCU ESP8266 hardware and DHT 22 sensor are set up and connected [23]. Next, the Blynk app is downloaded, installed, and conFig.d by creating a new project that generates an authentication code (Auth Token). The microcontroller is programmed using the Blynk Library to connect it to the WiFi network and the Blynk server, as well as to read data from the sensor and send it to the Blynk app [6]. Through the app, users can monitor the sensor data in real-time through various pre-conFig.d widgets and can also set notifications based on certain conditions for more effective monitoring.



(a) (b)

Fig. 6. Monitoring via Blynk application on Smartphone (a) at 10:00 am, and (b) at 7:27 pm.

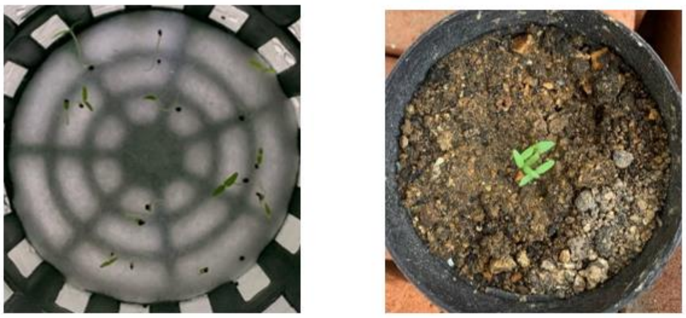
Fig. 6 illustrates the output generated by the P controller when the system is disturbed. In the visualization of the graph, it can be seen that when the humidity is above the setpoint value of 92%, the PWM value consistently decreases, dropping from 128 to 108 and increasing back to 128 as the humidity approaches the setpoint value. On the other hand, when the humidity is below the setpoint value of 92%, the PWM value has a consistent increase, rising from 128 to 155 and falling back to the value of 128 as the humidity approaches the setpoint value. This action aims to regulate the spread of water vapor from the mist maker so that it is evenly distributed throughout the root chamber. The rotational speed of the 12V DC fan is adjusted according to the PWM level generated by the output, thus ensuring that the humidity remains stable at the steady state value of 92%.

2.2 Testing planting results

The difference in planting using the fogponics method and the traditional method can be seen in Figs 7(a) and 7(b). Fig. 7(a) shows spinach seedlings planted on the first day, while part of Fig. 8 shows the fifth day after planting. Visually, the growth of the traditional method is faster and superior to the fogponik method, as seen from the larger size and faster growth of the spinach leaves. The possible cause of this result is that the spinach seeds used are specialized for soil growing media, which makes them more suitable for the traditional method. In addition, the treatments applied in the traditional method and the fogponics method differ in several important aspects. For example, the fogponik method may suffer from a lack of optimal sunlight as well as insufficient monitoring. These factors collectively contribute to the superiority of the traditional method over the fogponik method in spinach growth.

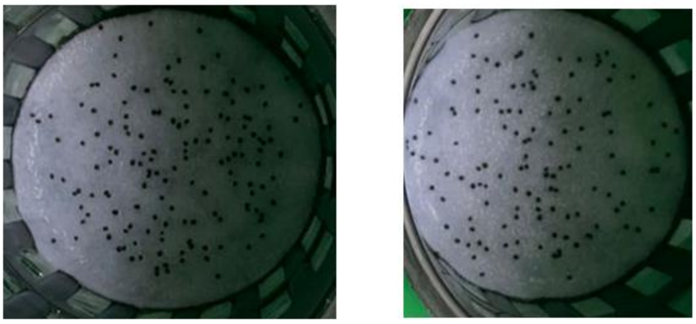
First day of planting spinach seeds in different pots (Fig. 8(a). Fig. 8(b) shows the growth of spinach plants, which have a similar and uniform pattern in each pot; this shows that there are even nutrients in each plant pot.

(a) 1st day

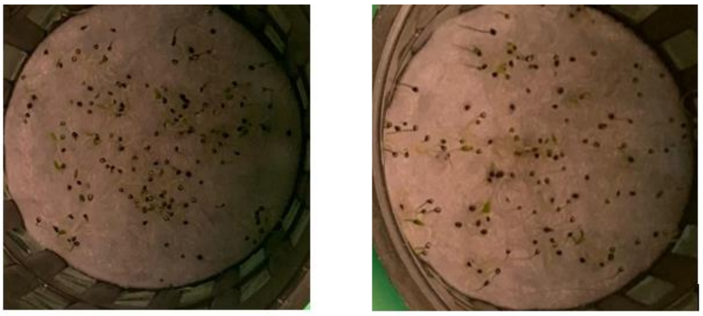


(b) 5th days

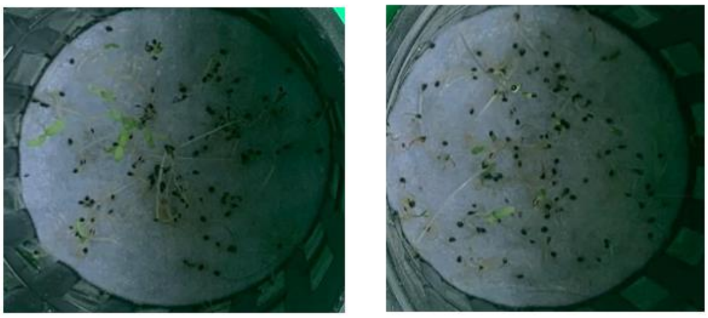
Fig. 7. Fogponic method in left and traditional method in right by different days.



(a) 1st day.



(b) 5th days



(c) 21st days

Fig. 8. Days and left and right pots are different pots.

Plants experience visual symptoms of wilting on day 15, the stems begin to curl and the leaves turn yellow, and conditions worsen on day 21 Fig. 8(c), where more plants wilted and few survived. This could be due to the equipment not operating for a full 24 hours due to overloading, so the nutrient solution mist in the 30-liter chamber was not evenly distributed throughout the chamber. As a result, the plants did not get enough nutrients, causing the plants to wilt. In addition, the prototype was placed indoors, which resulted in the plants being deprived of sunlight, which also contributed to the wilting conditions. The lack of sunlight necessary for photosynthesis inhibits plant growth, exacerbating the problems caused by the uneven distribution of nutrient mist.

The advantage of fogponic is its ability to carry out all stages of crop cultivation, from seeding to harvesting, in a single growing medium. This increases the efficiency and consistency of plant growth, making it a practical and effective cultivation option.

4 Conclusion

This study demonstrates the successful implementation of a mechanical air circulation system integrated with PID control to regulate temperature and humidity in fogponic spinach cultivation. The fan, as a key mechanical component, effectively maintains the root chamber environment, keeping the temperature below 30°C and stabilizing humidity at 92%. The system achieves reliable performance with different control parameters (P, PI, PD), ensuring optimal environmental conditions for plant growth.

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