TEPIAN Vol. 5 No. 4 (December 2024) 150-157 p-ISSN 2721-5350 e-ISSN 2721-5369
https://doi.org/10.51967/tepian.v5i4.3157 © 2024 Tepian Politeknik Pertanian Negeri Samarinda

Hydroponic System with Integrator Modified on PI Controller for Nutrient and Water Regulation

Ihsan Auditia Akhinov*
Electrical Engineering, Politeknik Negeri Jakarta,
Depok, 16425, Indonesia
ihsan.auditia.akhinov@elektro.pnj.ac.id

Nuralam
Electrical Engineering, Politeknik Negeri Jakarta,
Depok, 16425, Indonesia
nuralam@elektro.pnj.ac.id

Sri Lestari Kusumastuti
Electrical Engineering, Politeknik Negeri Jakarta,
Depok, 16425, Indonesia
sri.lestarikusmastuti@elektro.pnj.ac.id

Bernadeta Siti Rahayu Purwanti
Electrical Engineering,
Politeknik Negeri Jakarta,
Depok, 16425, Indonesia
rahayu.purwanti@elektro.pnj.ac.id

Adjie Nur Fadhilah
Electrical Engineering,
Politeknik Negeri Jakarta,
Depok, 16425, Indonesia
adjie.nur.fadhilah.te21@mhsw.pnj.ac.id

Submitted: 2024-09-25; Accepted: 2024-10-25; Published: 2024-12-08

Abstract**—** This study developed a hydroponic control system to regulate nutrient concentration (PPM) and water volume using a Proportional-Integral (PI) controller. The PI controller was chosen for its simplicity and effectiveness in systems that do not require fast response times. A trial-and-error method was used to tune the Kp and Ki values, which were implemented in an ATMega328 microcontroller. The system consists of one AC pump and two DC pumps: DC Pump-1 controls the PPM by supplying liquid fertilizer, while DC Pump-2 regulates the water volume. The results showed that modifying the PI controller with an integrator limitation improved performance. For PPM control, a limit of 13000 with Kp = 2 and Ki = 0.01 resulted in a 0.5% error, 56.8-second rise time, and a 4.8% overshot. For water level control, a limit of 12000 with Kp = 100 and Ki = 0.16 yielded a 3.25% error, 2% overshot, and a 65.4-second rise time. The test results demonstrated that the use of AB Mix can be reduced by up to 26% compared to a conventional PID, with an initial PPM value of around 350.

Keywords**—** Automated Farming**,** Hydroponic System, Integrator, PID, PPM

I. Introduction

The growth of hydroponic plants requires a nutrient solution absorbed by the plant roots through water media (Kularbphettong et al., 2019). The study claims that hydroponic methods are superior compared to traditional farming methods. This is because the growth of plants is conditioned by water and nutrients, allowing for faster growth and better harvest yields.

The information from the research (Suseno et al., 2020) highlights that maintaining the stability of nutrient concentration measured in Parts Per Million (PPM) and the water level in the reservoir tank remains a significant challenge. Stability is crucial to ensure accurate nutrient absorption so that plant growth is not hindered. PPM regulation is achieved by controlling the on-off duration of the liquid fertilizer connected to the pump (M Shetty et al., 2021), (Fakhrurroja et al., 2019). On the other hand, according to (Yong & Ibrahim, 2020), (Thakur et al., 2023), stability can also be maintained through the adjustment of pump voltage.

Challenges in hydroponic research are continuously evolving, leading to the development of a system to control PPM parameters in water using PID control (Chowdhury et al., 2021). This differs from the claims made in (Kurniawan, 2020), which state that the response characteristics of output differ between PI and PID controllers, depending on the type of actuator being controlled. The output of the PI controller is stable for systems that do not require fast rise times, while the PID response (Wang, 2020) is better in terms of rise time and recovery.

The error obtained is the difference between the established reference detection and the output from the sensor detection in the PI control. This error value is processed into the output voltage of the PI, which becomes the input variable for DC Pump-1 and DC Pump-2. Meanwhile, the PI output signal regulates the operation of the actuators.

The research (Huba et al., 2021) produces Kp and Ki values as parameters for the PI controller, obtained using the Ziegler-Nichols method. The PI controller with these Kp and Ki values regulates the speed of the DC motor according to the established reference. The research concept can be implemented in hydroponic systems to control PPM parameters and water flow. The PI controller is applied to manage both PPM and water level because it is simpler and suitable for systems that do not require rapid response times. A hydroponic system using a PI controller can optimize the use of a single pump and reduce excessive PPM or water levels during overshot events.

The application of a conventional PI controller on pumps to increase volume can result in output responses that experience overshot and oscillation. When the output response exceeds the reference or generates a negative error (reference-output), the actuator will reduce the excess concentration. This reduction can lead to the wastage of dissolved liquid fertilizer. Therefore, it is necessary to modify the PI controller to minimize overshot and oscillation, thereby improving the efficiency of fertilizer and water usage.

Based on the results of several previous studies (Lorenzetti & Weiss, 2023) , a modified PI control system needs to be developed specifically for regulating PPM and water volume parameters. The control system consists of a microcontroller, one AC pump, two DC pumps, and hydroponic modules, which include a main tank and a liquid fertilizer tank. DC Pump-1 regulates the PPM levels by supplying liquid fertilizer, while DC Pump-2 controls the water volume. The PI control program utilizes Kp and Ki values obtained through a trial-and-error method. The Kp and Ki parameters are implemented as instructions in the ATMega328 microcontroller, allowing for the automatic control of both PPM and water volume parameters.

II. Literature Review

Green lettuce (Lactuca sativa L. Grand Rapids) is a type of leafy vegetable that is often cultivated for consumption, especially in salads. This plant grows well in hydroponic systems and requires the right nutrients to achieve optimal growth. Green lettuce is rich in vitamins and minerals, making it a healthy choice in the diet (Ramaidani et al., 2021).

The type of vegetable plant, green lettuce (Lactuca sativa L. Grand Rapids), is cultivated for ready-to-eat food, such as salads. The cultivation of green lettuce thrives optimally in hydroponics when provided with the right nutritional needs, in addition to being rich in vitamins and minerals (Ariananda et al., 2020), making it a healthy food choice in the diet. According to, the use of liquid fertilizer AB MIX is considered the best nutrient for lettuce growth.

The accuracy of fertilizer usage as nutrients through water or growing media requires the regulation of circulation and flow rate. Water flow regulation is developed using a PID control system, which consists of proportional (P), integral (I), and derivative (D) components for automation systems. Automatically, the system achieves and maintains the setpoint value while minimizing errors. The purpose of using PID control is to achieve and sustain the setpoint value in the system while minimizing errors, as outlined in [Comparison of Fuzzy-PID and PID Controller for Speed Control of DC Motor using LabVIEW].

The use of PID control, as outlined in [Comparison of Fuzzy-PID and PID Controller for Speed Control of DC Motor using LabVIEW], maintains the reference value by minimizing errors to achieve an output that aligns with the reference. The formula for the PID controller (PI Controller of Speed Regulation of Brushless DC Motor Based on Particle Swarm Optimization Algorithm with Improved Inertia Weights) is discussed in the study (Proportional-Integral) and is presented in equation (1).

$$u(t) = K_p . e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt} \qquad (1)$$

$u(t)$: Control Signal
K_p : Proportional coefficient
K_i : Integral coefficient
d : Derivative coefficient
e(t) : Error at time
$\int_0^t e(\tau)\, d\tau$: Integral of the error from time 0 to t
$\frac{de(t)}{dt}$: Differential of the error with respect to time

III. Research Methods

The stages of designing the device are: (1) preparation of the hydroponic growing medium, (2) installation of electronic modules/components into a control system, (3) data collection, and (4) observation of the growth trends of green lettuce.

The design of the hydroponic growing medium resembles an irrigation system with water flowing through PVC pipes, featuring holes for growing lettuce plants. Nutrients from AB Mix liquid are mixed with water in a ratio of 2:1 and introduced into the main tank (capacity 1.5 L). This nutrient solution flows together with the circulating water in the growing medium using DC Pump-1 (PPM-pump). The PPM value is measured by a Total Dissolved Solids (TDS) sensor installed in the main tank.

The design of the hydroponic growing medium resembles an irrigation system with water flowing through PVC pipes, featuring holes for growing lettuce plants. Nutrients from AB Mix liquid are mixed with water in a ratio of 2:1 and introduced into the nutrient tank (capacity 1.5 L). The solution in the nutrient tank is pumped using DC Pump-1 (PPM-pump) to the main tank. The PPM value is measured by a Total Dissolved Solids (TDS) sensor installed in the main tank.

The design of the device aims to provide a solution to the issues encountered with the use of PI control in previous research, which utilized two pumps: one for inflowing water and another for outflowing water. This study, however, employs only one pump for inflow without a drainage pump, necessitating the addition of water from the water pump to counteract excess PPM values. Therefore, it is essential to engineer the PI controller to achieve minimal overshoot and short output oscillations. This concept is applied to both the PPM pump and the water pump.

The method used for regulating water volume employs two sensors. The ultrasonic sensor detects the water level in the main tank, and the detection results provide feedback data. The second sensor is a flow sensor, which measures the volume of water that has passed through the water pump. The combination of these two sensors feeds into a single DC pump (water pump) within the PI system. The output from the PI controller is then used to activate the water pump.

The ATMega328 microcontroller processes the PI control system, receiving reference inputs and comparing them with the PPM detection results from the TDS sensor, the ultrasonic sensor, and the Real-Time Clock (RTC).

The output of the PI calculations in the microcontroller is in the form of a PWM wave, which is forwarded to the L298N, functioning as a driver for the DC pump. The Kp and Ki parameters for the PI controller are obtained through tuning. The DC Pump-1 (PPM-PUMP) is responsible for delivering the AB mix liquid to the main tank. Similarly, DC Pump-2 functions to supply clean water to the main tank. A representation of this system can be seen in figure 1.

The modification of the PI controller aims to reduce oscillations and overshot caused by the accumulation of integrator properties, which leads to wastage of fertilizer and water when the output exceeds the reference value. When the output exceeds the reference, an action is taken to add water to lower the PPM concentration. The higher the overshot, the more fertilizer and water are consumed.

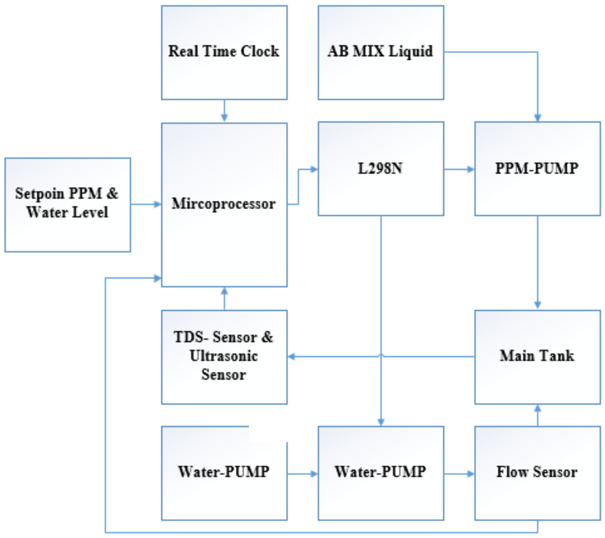


Figure 1. Block Diagram of the PI Control System for Hydroponic Plants.

The program algorithm for the PPM concentration controller is shown in figure 2. The PI method is used to operate one of the pumps, either the PPM-PUMP or the water pump. Both pumps do not operate simultaneously; the activation and deactivation of each pump depend on the output value from the PI calculations. If the PI calculation result is greater than zero, the PPM pump will turn on. Conversely, if the PI calculation result is negative, the water pump will turn on. The flow rate of the fluid depends on the PI calculation value that is converted into the input voltage for each pump.

The algorithm for the water volume controller is similar to that of the PPM concentration controller, but there are some differences. The water volume algorithm is represented in Figure 3. When the PI calculation result is negative, both pumps will turn off, and the parameters on the PI are set to minimize overshot, even to the point of having no overshot at all.

The water volume and PPM concentration control systems can be said to be in an overdamped state with very small error values. The algorithms for controlling PPM concentration and water volume operate alternately, with each algorithm being active for one hour. This is represented in figure 4. The time reference input process is conducted using the Nextion HMI. The Real-Time Clock (RTC) is used to obtain the actual time. To determine the plant age in the hydroponic system, the reference value is compared with the RTC.

IV. RESULT & DISCUSSION

The realization of the tool can be seen in figure 5. Generally, it consists of three tanks: the nutrient tank, the main tank, and the water source tank. The main equipment, such as the RTC, microprocessor, and power supply, is in the panel box.

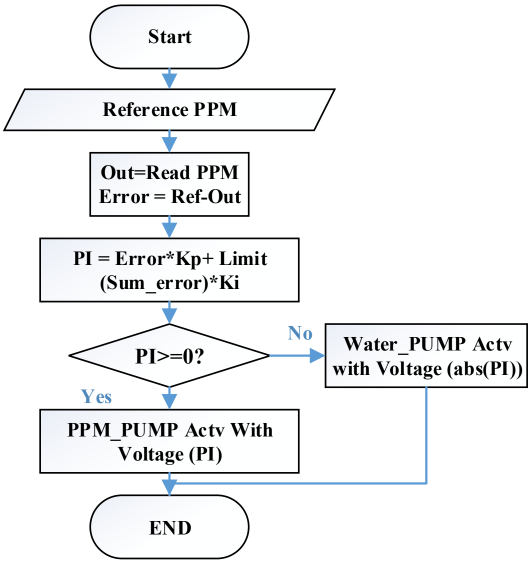


Figure 2. Flowchart of PI Controller for PPM Concentration

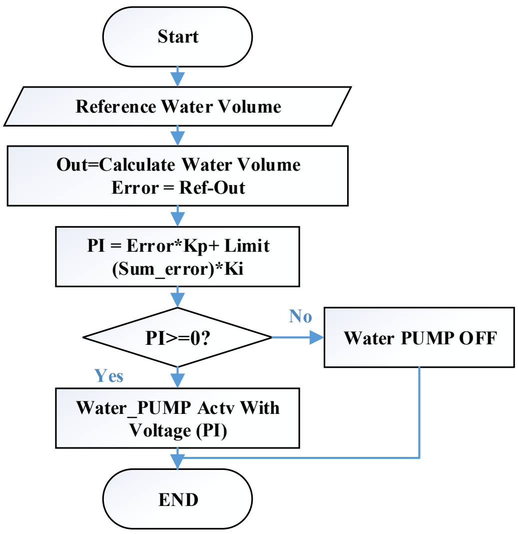


Figure 3. Flowchart of PI Controller for Water Volume

Akhinov, I. A., Nuralam, Kusumastuti, S. L., Purwanti, B. S. R., & Fadhilah, A. N. (2024). Hydroponic System with Integrator Modified on PI Controller for Nutrient and Water Regulation. TEPIAN, 5(4). https://doi.org/10.51967/tepian.v5i4.3157

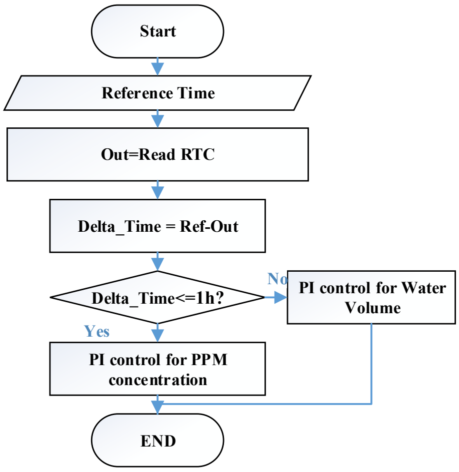


Figure 4. Flowchart of PI Controller for Water Volume

This system operates starting from the microcontroller, which reads the TDS and ultrasonic sensors. The sensor values are compared with the reference PPM and water volume. The results of the comparison are calculated by the PI controller, whose output controls the PPM pump and the water pump. The PPM pump transfers water from the nutrient tank to the main tank, while the water pump circulates water from the clean water tank to the main tank. The AC pump continuously circulates water from the main tank to the hydroponic kit.

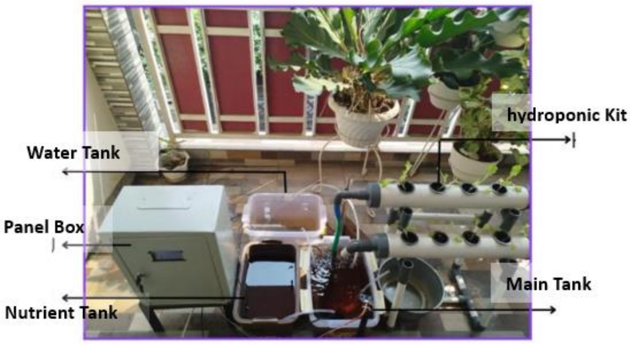


Figure 5. Realization of the Hydroponic System

This system operates starting from the microcontroller, which reads the TDS and ultrasonic sensors. The sensor values are compared with the reference PPM and water volume. The results of the comparison are calculated by the PI controller, whose output controls the PPM pump and the water pump. The PPM pump transfers water from the nutrient tank to the main tank, while the water pump circulates water from the clean water tank to the main tank. The AC pump continuously circulates water from the main tank to the hydroponic kit.

A. Determination of PID Parameters

This system operates starting from the microcontroller, which reads the TDS and ultrasonic sensors. The sensor values are compared with the reference PPM and water volume. The results of the comparison are calculated by the PI controller, whose output controls the PPM pump and the water pump. The PPM pump transfers water from the nutrient tank to the main tank, while the water pump circulates water from the clean water tank to the main tank. The AC pump continuously circulates water from the main tank to the hydroponic kit.

The tuning results for Kp, Ki, and Kd, along with the response parameters for PPM control, are shown in Table 1 with set poin 600 PPM. In the first row of Table 1, the values of Kp, Ki, and Kd produce a signal with a high overshot of 28%, indicating an excess dosage of ABMIX in the main tank. This excess can be reduced by dilution with clean water pumped by the DC2 pump, but this leads to wastage of both water and fertilizer.

The tuning results in the second row of Table 1 show a long rise time, causing the integrator value to reach hundreds of thousands. This leads to high overshot and settling time. To address this, the integrator was modified by setting a limit of 40,000. Although the overshoot percentage decreased, oscillation remained high from the perspective of rise time. As a result, fertilizer and clean water were still wasted during the oscillation period.

The tuning results in the third row of Table 1 show an overshot of 4.8% and a low settling time from the perspective of rise time. In this experiment, in addition to eliminating the derivative, the integrator limit was adjusted to 13,000. Therefore, the Kp and Ki parameters without the derivative from the third row of Table 1 were selected for controlling the concentration of liquid fertilizer (PPM) dissolved in water.

The same approach is used to determine the values of Kp, and Ki in water volume control with setpoint 2 L. These parameters are obtained through a tuning process, with results such as rise time, peak time, overshot, and settling time presented in Table 2. The water volume control only involves one DC pump, the water pump. If the PI calculation yields a positive value, the water pump adds clean water to the main tank. For negative PI calculation results, no action is taken.

The output response for each experiment in Table 1 can be seen in figure 6. Figure 6a shows the result with overshot and oscillation, figure 6b displays a small overshot with slight oscillation, and figure 6c shows a small overshot without oscillation. The experiment using the parameters from the first row of Table 2, shown in figure 7a, indicates the highest rise time and overshot compared to the other three experiments. Next, the experiment with the parameters from the second row of Table 2 resulted in the output response seen in figure 7b, with a drastic reduction in rise time and overshot. The final experiment produced better values for overshot, rise time, peak time, and settling time compared to the other three experiments in Table 2, as can be seen in figure 7c.

The results of testing various control parameters for the PPM concentration controller, as summarized in Table 3. The test results are based on the values of Kp, Ki, and Kd, as well as the integrator limits set on the microcontroller, as shown in Table 1. The results of the third test indicate that using the final water volume to reduce excessive PPM concentration, as outlined by the algorithm in Figure 2, led to a reduction of water usage to 13.7 liters when the integrator limits were applied, compared to no limits.

Akhinov, I. A., Nuralam, Kusumastuti, S. L., Purwanti, B. S. R., & Fadhilah, A. N. (2024). Hydroponic System with Integrator Modified on PI Controller for Nutrient and Water Regulation. TEPIAN, 5(4). https://doi.org/10.51967/tepian.v5i4.3157

Additionally, the results without limits showed a disadvantage in calculating the final water volume, where the water level exceeded the capacity of the main tank. The final PPM concentration read by the sensor differed by 0.025% from the reference, which is acceptable given that the PPM concentration range for watercress is 560-840 (Marisa et al., 2021).

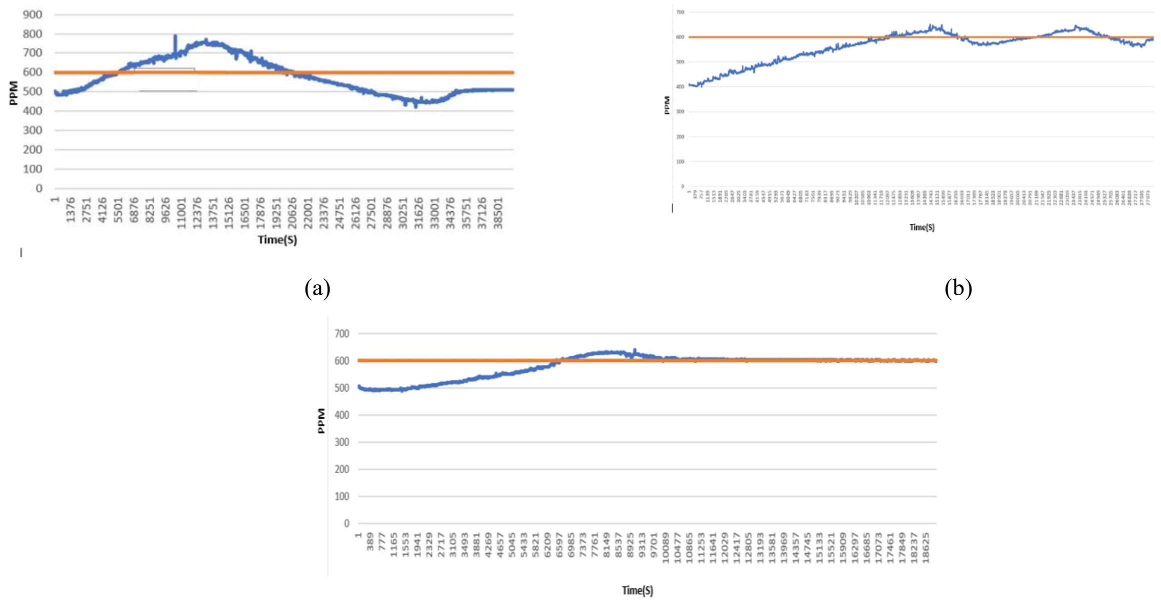
The tests also evaluated the remaining volume of liquid fertilizer in each experiment. The results show the amount of fertilizer used from a total of 10 liters. The best result, as shown in row 3 of Table 3, indicates a remaining liquid fertilizer volume of 8.84 liters, meaning that only 1.16 liters, or 11.6%, was used. It should be noted that the smaller the remaining volume, the more liquid fertilizer was utilized in the test. This modified PI reduced excess liquid fertilizer usage by approximately 26% compared to the unmodified PID.

Table 1. PID Parameter Experiment with Integrator Modification for PPM Control

No	Kp	Ki	Kd	Limit I	tr (sec)	tp (sec)	Overshot (%)	ts (sec)
1	3,1	0,14	422,7	off	47,04	112,6	28	162,2
2	3,1	0,14	422,7	±40000	106,4	128,3	6,5	205,4
3	2	0.01	-	±13000	56,8	68,4	4,8	80,2

Table 2. PID Parameter Experiment with Integrator Modification for Water Volume Control

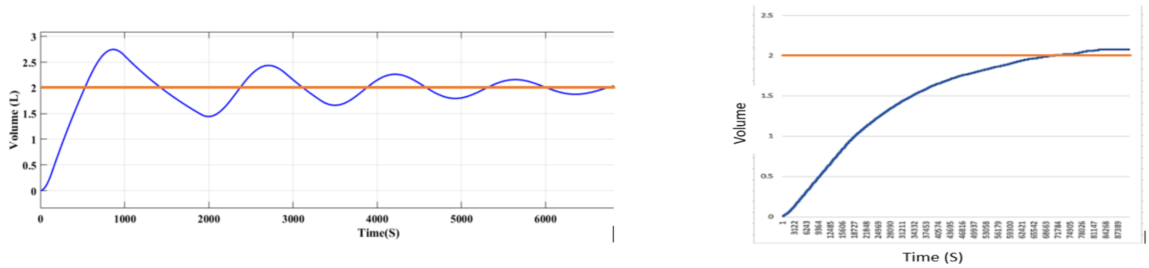
No	Kp	Ki	Kd	Limit I	tr (sec)	tp (sec)	Overshot (%)	ts (sec)
1	5,79	0,0002	-	off	518	858	35,5	7000
2	100	0,02	-	±12000	61,4	62,4	4	89,7
3	100	0.016	-	±12000	65,4	71,4	2	87,2



(a) (b)

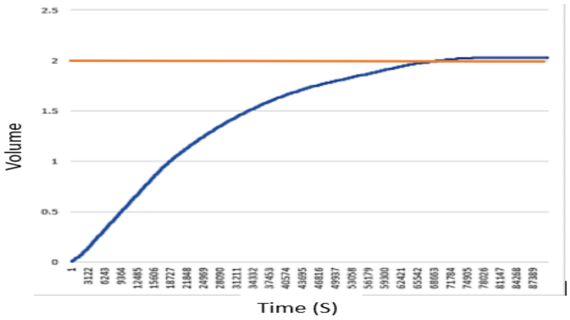
(c)

Figure. 6. Test Response Results for PID Tuning Variations in Controlling PPM Values: a) Kp=3.1, Ki=0.14, Kd=422.7 b) Kp=3.1, Ki=0.14, Kd=422.7 with an integral limit of 40,000 c) Kp=2, Ki=0.01 with an integral limit of 13,000.



(a) (b)

Akhinov, I. A., Nuralam, Kusumastuti, S. L., Purwanti, B. S. R., & Fadhilah, A. N. (2024). Hydroponic System with Integrator Modified on PI Controller for Nutrient and Water Regulation. TEPIAN, 5(4). https://doi.org/10.51967/tepian.v5i4.3157



(c)

Figure. 7. Test Response Results for PID Tuning Variations in Controlling PPM Values: a) Kp=3.1, Ki=0.14, Kd=422.7 b) Kp=3.1, Ki=0.14, Kd=422.7 with an integral limit of 40,000 c) Kp=2, Ki=0.01 with an integral limit of 13,000.

Table 3 Testing each controller parameter against the PPM concentration controller with respect to the final PPM response and water volume.

No	Kp	Ki	Kd	Limit	PPM reference	Initial PPM	Initial Water Volume (L)	Liquid fertilizer Tank (L)- Max 10 L	Final PPM	The usage of fertilizer %	Final Water Volume(L)	Status
1	3,1	0,14	422,7	0	600	332	12.73	6.23	601	37.7	22	Overload
2	3,1	0,14	422,7	14000	600	351	12.71	8.25	620	17.5	16,9	-
3	2	0,01	-	13000	600	340	12.75	8.84	615	11.6	15.8	-

B. *Results of PI Implementation*

The implementation of the PI method for controlling PPM and water volume is shown in Figure 8, with a reference PPM value of 700 and a water volume of 56%. If calculated using the simple volume formula for a rectangular tank (main tank) with a length of 38 cm, a width of 24 cm, and a height of 25 cm, the height read by the ultrasonic sensor as a reference is approximately 14 cm. For PPM control, as shown in figure 8, an error of ±0.5% was observed. Meanwhile, for water level control, the error obtained was ±3.25%.

There are two factors that prevent the error value from reaching 0%. First, the presence of deadband voltage (0-1 V) in the DC pump. Referring to previous research, the effect of this deadband impacts the linear state in the control system, which can lead to inaccuracies in system response (Pires de Souza & Zelir Azzolin, 2020). This deadband occurs when the control signal does not produce changes in the output, thereby slowing the system's response to the required input changes. Second, the limitation of the integrator value can also help convert an unstable system into a stable one (Lorenzetti & Weiss, 2023). In the context of this experiment, limits on the integrator function to restrict error accumulation help reduce the likelihood of excessive oscillations.

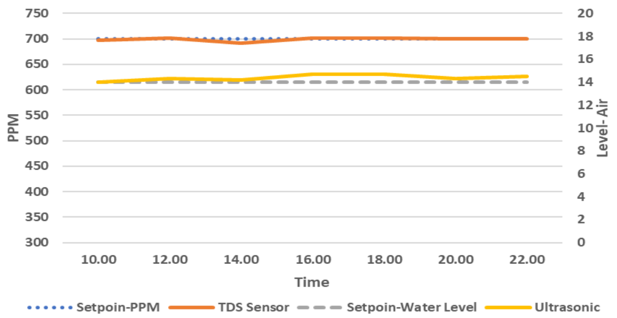
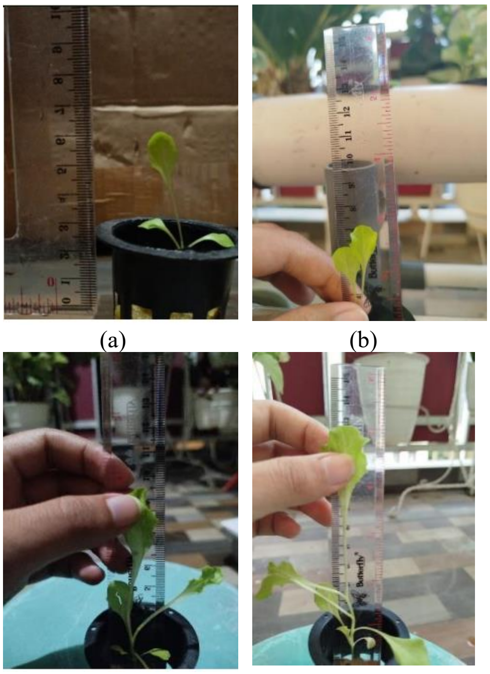


Figure 8. Results of PI Implementation for Controlling PPM and Water Flow Rate.

The modification of the integrator factor in the tests leads to the hypothesis that the integrator's accumulation from the sum of error values over time can reach a high value. This high value, when multiplied by another high number, will result in a high final value. Conversely, if multiplied by a small number, the integrator's result will decrease. Therefore, the variation of the Ki value, which depends on the accumulated error that occurs, will optimize the calculation results, as explained in previous research(Lumpur et al., 2020).



(a) (b) (c) (d)

Figure 9. Results of PI Implementation on Plants: a) 5 Days Old - Height: 61 mm b) 10 Days Old - Height: 71 mm c) 15 Days Old - Height: 101 mm d) 20 Days Old - Height: 121 mm.

The hydroponic system was tested on plants and observed every 5 days, as shown in figure 9. The test results on green lettuce plants showed a significant increase in height over 20 days, with no leaf drops or yellowing. This increase in plant height indicates that the hydroponic environment provided optimal conditions for growth. Furthermore, other studies have shown that one of the common signs of nutrient overload is yellowing leaves, often caused by excessive salt accumulation in the growing (Edaroyati et al., 2024; Krasilnikov & Taboada, 2022). Therefore, the findings in this study, which show no signs of toxicity such as leaf drop or yellowing, support the system's efficiency in maintaining an optimal nutrient balance. The success of this hydroponic system in maintaining the health of green lettuce plants during the trial period serves as an important indicator of effective and reliable nutrient management.

V. Conclusion

The conclusion of this study indicates that modifying the PI controller with integrator limitations produces good performance for controlling PPM and water levels. PPM control with an integrator limit of 13,000, Kp = 2, and Ki = 0.01 resulted in an error of 0.5%, a rise time of 56.8 seconds, a settling time of 80.2 seconds, and an overshot of 4.8%. The test results show that the use of AB Mix can be reduced by up to 26% compared to conventional PID, with an initial PPM value of around 350. Water volume control with Kp = 100, Ki = 0.16, and an integrator limit of 12,000 resulted in a recorded error of 3.25%, a 2% overshot, a rise time of 65.4 seconds, and a settling time of 87.2 seconds. Monitoring over 12 hours showed error rates consistent with those obtained during tuning, while application over 20 days demonstrated healthy plant growth without yellowing leaves. Therefore, the modification of the PI with fixed parameters needs to be compared with adaptive PI, which can adjust Kp and Ki based on output response and error values.

References

Ariananda, B., Nopsagiarti, T., Mashadi, D., Program, M., Agroteknologi, S., Pertanian, F., Program, D., Islam, U., & Singingi, K. (2020). Pengaruh Pemberian Berbagai Konsentrasi Larutan Nutrisi Ab Mix Terhadap Pertumbuhan Dan Produksi Selada (Lactuca Sativa L.) Hidroponik Sistem Floating. Green Swarnadwipa : Jurnal Pengembangan Ilmu Pertanian, 9(2), 185–195. https://ejournal.uniks.ac.id/index.php/GREEN/article/view/750

Chowdhury, M., Ali, M., Rasool, K., Jeong, J. H., Choi, C. H., Han, M. W., Ko, H. J., & Chung, S. O. (2021). Identification of PID parameters for system-specific nutrient mixing control for ISE-based hydroponic nutrient management. Acta Horticulturae, 1312(June), 567–574. https://doi.org/10.17660/ActaHortic.2021.1312.80

Edaroyati, P., Wahab, M., Che-othman, M. H., & Al-, A. R. M. (2024). Managing Nitrogen Toxicity in the Soilless Culture System : A Review. 15(1985), 11–26.

Fakhrurroja, H., Mardhotillah, S. A., Mahendra, O., Munandar, A., Rizqyawan, M. I., & Pratama, R. P. (2019). Automatic pH and Humidity Control System for Hydroponics Using Fuzzy Logic. 2019 International Conference on Computer, Control, Informatics and Its Applications (IC3INA), 156–161. https://doi.org/10.1109/IC3INA48034.2019.8949590

Huba, M., Chamraz, S., Bisták, P., & Vrančić, D. (2021). Making the PI and PID Controller Tuning Inspired by Ziegler and Nichols Precise and Reliable. Sensors, 21, 6157. https://doi.org/10.3390/s21186157

Krasilnikov, P., & Taboada, M. A. (2022). Fertilizer Use , Soil Health and Agricultural Sustainability. 16–20.

Kularbphettong, K., Ampant, U., & Kongrodj, N. (2019). An Automated Hydroponics System Based on Mobile Application. International Journal of Information and Education Technology, 9(8), 548–552. https://doi.org/10.18178/ijiet.2019.9.8.1264

Kurniawan, E. (2020). Analysis and Simulation of PI and PID Control Systems Using Xcos Scilab. Journal of Technomaterials Physics, 2, 108–116. https://doi.org/10.32734/jotp.v2i2.5402

Lorenzetti, P., & Weiss, G. (2023). Saturating PI Control of Stable Nonlinear Systems Using Singular Perturbations. IEEE Transactions on Automatic Control, 68(2), 867–882. https://doi.org/10.1109/TAC.2022.3147167

Lumpur, K., Motakabber, S. M. A., Lumpur, K., Alam, A. H. M. Z., Lumpur, K., Nordin, N., & Lumpur, K. (2020). Adaptive PID Controller Using for Speed Control of the BLDC Motor. 168–171.

M Shetty, H., Pai K, K., Mallya, N., & Pratheeksha. (2021). Fully Automated Hydroponics System for Smart Farming. International Journal of Engineering and Manufacturing, 11(4), 33–41. https://doi.org/10.5815/ijem.2021.04.04

Marisa, M., Carudin, C., & Ramdani, R. (2021). Otomatisasi Sistem Pengendalian dan Pemantauan Kadar Nutrisi Air menggunakan Teknologi NodeMCU ESP8266 pada Tanaman Hidroponik. Jurnal Teknologi Terpadu, 7, 127–134. https://doi.org/10.54914/jtt.v7i2.430

Pires de Souza, L., & Zelir Azzolin, R. (2020). Dead Zone Compensation in Direct Current Motors: A Review. 2010. https://doi.org/10.48011/asba.v2i1.1223

Ramaidani, R., Mardina, V., & Al Faraby, M. (2021). Pengaruh Nutrisi Ab Mix Terhadap Pertumbuhan Sawi Pakcoy Dan Selada Hijau Dengan Sistem Hidroponik. BIO-EDU: Jurnal Pendidikan Biologi, 6(3), 300–310. https://doi.org/10.32938/jbe.v6i3.1223

Suseno, J. E., Munandar, M. F., & Priyono, A. S. (2020). The control system for the nutrition concentration of hydroponic using web server. Journal of Physics: Conference Series, 1524(1). https://doi.org/10.1088/1742-6596/1524/1/012068

Thakur, P., Malhotra, M., & Bhagat, R. M. (2023). IoT-based Monitoring and Control System for Hydroponic Cultivation: A Comprehensive Study. https://doi.org/10.21203/rs.3.rs-2821030/v1

Wang, L. (2020). PID Control System Design and Automatic Tuning Using MATLAB/Simulink.

Yong, W. X., & Ibrahim, A. N. (2020). Field Study of PID Parameter Tuning Investigation in Peristaltic Dosing Pump Control for Use in Automated Fertilizer Mixing System. Mekatronika, 2(2), 13–22. https://doi.org/10.15282/mekatronika.v2i2.6742