# Design and testing of a nutrient solution control system for soilless culture using mathematical models

**Sirinya Chaila[1], Chaiyong Soemphol[1,2]**
[1]Department of Electrical and Computer Engineering, Faculty of Engineering, Mahasarakham University, Maha Sarakham, Thailand
[2]Research Unit for Electrical and Computer Engineering Technology (RECENT), Faculty of Engineering, Mahasarakham University, Maha Sarakham, Thailand

**Article Info**

***Article history:***

Received May 24, 2024
Revised Sep 11, 2024
Accepted Sep 30, 2024

***Keywords:***

Electrical conductivity
Linear regression
Mathematical model
Nutrient control
Soilless culture

**ABSTRACT**

The optimization of nutrient management is crucial for successful soilless plant cultivation, where precise control of fertilizer application significantly impacts plant growth. This research addresses the challenge of developing an effective nutrient control system tailored for soilless cultivation by focusing on regulating electrical conductivity (EC) levels in nutrient solutions. The proposed system utilizes mathematical models and linear regression techniques to manage the nutrient solution mixing ratio. To ensure accuracy, sensors were calibrated, achieving a 99.59% accuracy rate for pH measurement and 95.25% for EC measurement. Experimental validation of the system demonstrated that, with a target EC range of 1.5-2.3 mS/cm, a 10 L solution volume yielded a maximum error rate of 1.75% and an average error of 0.95%. In contrast, a 50 L solution volume showed a slight increase in maximum error rate to 2.89% and an average error of 2.08%. These results highlight the system's capability to precisely adjust EC levels using a defined linear regression model for AB liquid fertilizer ratios. In conclusion, the developed system effectively controls nutrient levels, demonstrating its potential for enhancing nutrient management in hydroponic farming applications.



***Corresponding Author:***

Chaiyong Soemphol
Research Unit for Electrical and Computer Engineering Technology (RECENT)
Faculty of Engineering, Mahasarakham University
Kantarawichai, Maha Sarakham, 44150, Thailand
Email: chaiyong.s@msu.ac.th

## 1. INTRODUCTION

Hydroponics is one approach to soilless culture that has garnered significant attention as a sustainable alternative to traditional soil-based agriculture. This is particularly so in consideration of diminishing farmland due to urbanization and increasing climate unpredictability. Soilless farming methods offers flexible and efficient means of cultivating crops hydroponically, by allowing plants to grow in nutrient-rich solutions instead of soil [1]. When compared with traditional farming, hydroponics can produce higher yields by exploiting not only the horizontal surface area, but also the vertical space above it, effectively increasing the number of plants per unit area, and might favor vertical farming to meet daily consumer demands for nutritious fresh products in and around densely populated areas [2]. The trend of controlled environment agriculture (CEA) has become increasingly prominent in hydroponics research. CEA ensures that hydroponic systems are protected from plant diseases, infestations, and unpredictable weather conditions. Despite its advantages, one of the primary challenges in hydroponic operation lies in the efficient and precise maintenance of the nutrient solution. Fluctuations in key growth parameters, such as electrical conductivity (EC) and pH levels, can adversely affect the growth of hydroponic plants. Sudden changes in the growth parameters such as ambient temperature, relative humidity, EC, and pH level negatively impact the growth of hydroponic plants [3]. Therefore, the nutrient solution control system is crucial for optimizing hydroponic farming, ensuring that plants receive the right balance of nutrients and pH levels [4]-[6].

Several studies have proposed automated nutrient control systems capable of regulating the distribution of nutrient solutions and maintaining ideal growth conditions [7]-[9]. The integration of the internet of things (IoT) has been suggested for hydroponic plants. These systems utilize various sensors and microcontrollers to monitor [10]-[12] and adjust nutrient levels [13]-[17]. However, it is not enough to control all of them, it must be used in conjunction with other algorithms such as IoT and K-nearest neighbors (KNN) that can controlling nutrient levels with over 90% accuracy [18] as well as combined with Bayesian network model which can monitor of light intensity, pH, EC, water temperature, and relative humidity as an accuracy of 84.53% [19]. Some research groups have successfully demonstrated the high potential of fuzzy logic for managing nutrient solution pH in hydroponics, achieving accuracy rates exceeding 90%, which has led to enhanced crop yields and more effective control mechanisms [20]-[25]. Additionally, control systems utilizing microcontrollers combined with convolutional neural networks (CNN) have shown promising results, with reported error values of 3.35% for nutrient control and 0.98% for pH control [26]. Furthermore, Recent research has investigated the application of linear regression techniques in the design of automated systems for monitoring and controlling nutrient levels and pH [27]-[31]. One study demonstrated the high accuracy of this approach, achieving a precision rate of 94.84% in various scenarios involving different reservoirs and set points, with an overall system accuracy of 89.37% [28]. Another study successfully illustrated that an EC adjustment equation derived from linear regression could maintain EC levels within the desired range. The accuracy of the system for pH control was reported at 95%, while for EC control, it reached 80.8% [29]. Additionally, a study developed an IoT-based control system utilizing multiple linear regression methods for managing nutrient solutions in hydroponics, achieving an overall accuracy of 92.42% [30]. These automated systems have demonstrated consistency and precision, which contribute to enhanced crop yields. However, it is noteworthy that some proposed systems have not achieved optimal accuracy levels. There remains a significant need for further improvements in system precision to ensure that nutrient levels are managed more effectively across various plant types.

In this work, we aim to design a high precision and accuracy of nutrient control system before using nutrient solution in the form of watering and distribution in the water system specifically for substrate culture, especially by controlling the value of EC of nutrients. We aim to use mathematical simulations to develop a linear regression model that can accurately regulate nutrient concentrations. By fine-tuning this system, we hope to contribute to the optimization of soilless farming practices and provide valuable insights for growers seeking to maximize their yields in non-soil environments. This paper is structured as follows: section 2, describe about system design and method which provides detailed information on the sensor calibration, the development of a mathematical simulation system for determining mixing ratios, the hardware system design and the control circuit configuration. Section 3 presents the experimental results and discussion, while section 4 concludes the paper.

## 2. SYSTEM DESIGN AND METHOD

The research methodology employed in this study is designed to follow a systematic as shown in Figure 1. The process initiates with the precise calibration of sensors to ensure that all subsequent measurements are both accurate and reliable, establishing a solid foundation for data collection. Once the sensors are calibrated, a mathematical simulation system is developed to create predictive models that simulate the behavior of the system under different conditions. The insights gained from these simulations are then used to inform the hardware design phase. During this phase, careful consideration is given to the selection and integration of components, resulting in a cohesive hardware architecture that aligns with the operational requirements identified through simulation.

After the hardware system is designed, attention turns to the development of the control circuit. This component is critical as it manages the hardware system's operations by processing input data from the sensors to ensure the system functions as intended. The control circuit is designed to handle sensor data effectively, enabling precise control over the hardware components. The methodology concludes with comprehensive system testing, which serves to validate the functionality and performance of the integrated system. This testing phase is crucial for identifying and addressing any discrepancies or potential improvements, ensuring the system meets all specified objectives. Upon successful completion of these tests, the research process is finalized, confirming that the system is fully operational and aligned with the project goals.

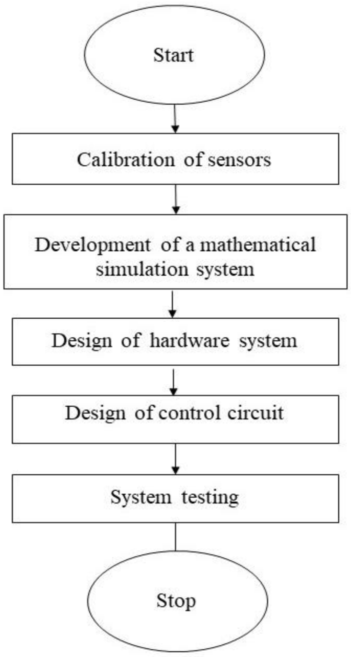


Figure 1. Methodology flowchart for system development

### 2.1. Calibration of sensors

Ensuring the accuracy and reliability of our system during testing was of paramount importance, necessitating calibration of all equipment. This calibration will serve to minimize errors and enhance the precision of our measurements. We employed two calibration methods by utilizing pH buffer powders and relying on a trusted reference device by using PCTestr35 multi-parameter as shown in Figure 2.

For pH sensor calibration, we employed buffer powders with distinct pH values of 4.01, 6.89, and 9.14. Conducting 20 calibration tests for each pH value ensured consistent and reliable results. The results are shown in Figure 2(a). It was found that the values obtained from the measurements were close to the reference values, culminating in an impressive accuracy rate of 99.59%. In calibrating the EC sensor, we utilized the PCTestr35 multi-parameter device. As with the pH calibration process, we executed 20 calibration tests, concentrating on one value at a time. The results are shown in Figure 2(b). The values obtained from the sensors used were not much different from those from standard instruments. This sensor yielded an accuracy rate of 95.25%.

By following these rigorous calibration protocols, we are confident in the reliability and accuracy of our system's sensors. These methods ensured that our testing data was both trustworthy and consistent, allowing for meaningful analysis and interpretation.

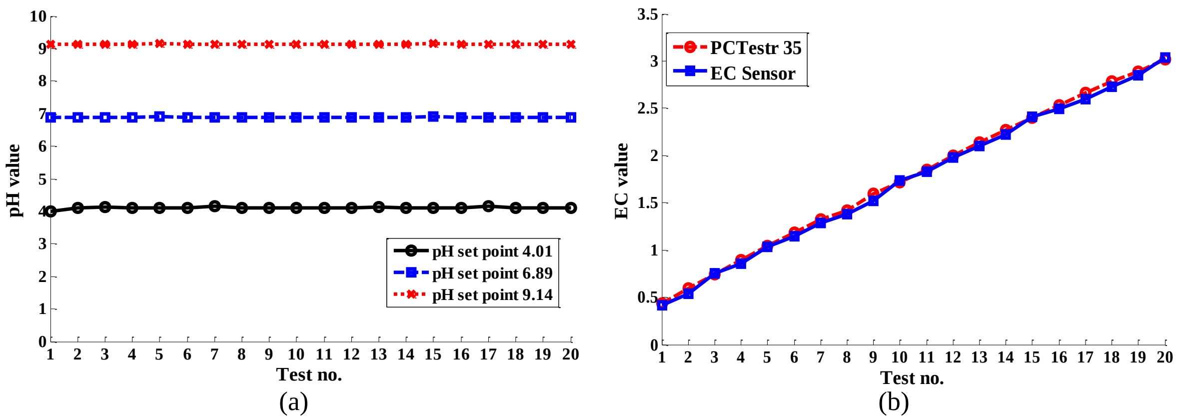


Figure 2. Results of calibration of sensor (a) pH sensor and (b) EC sensor

**2.2. Development of a mathematical simulation system for mixing ratios**

In this part of the study, we wanted to design a reliable mathematical simulation system for determining mixing ratios. We conducted a series of experiments to establish the relationship between EC and the addition of AB liquid fertilizer. First, the experiment involved incrementally adding 1 ml of AB liquid fertilizer to a 1 L solution, with 10 replicates, to create a robust dataset. Our objective was to derive an equation that would accurately predict the appropriate mixing ratio based on changes in electrical conductivity.

Subsequently, the collected data were analyzed to assess the correlation between the quantity of AB liquid fertilizer and the resulting EC in a 1 mL solution, as illustrated in Figure 3. By applying linear regression techniques, we derived the equation $y = 4.4614x^{1.6302}$ with an $R^2$ value of 0.9924. This equation serves as the basis for determining the system's operational parameters needed to control the release of the AB solution into the mixture. By expressing this relationship in a linear form, the system can map the required EC values as indicated in Equation 1. In addition, this strong correlation allowed us to develop a precise mathematical model for determining the exact amount of AB liquid fertilizer needed to achieve a specific conductivity target for any given volume of water.

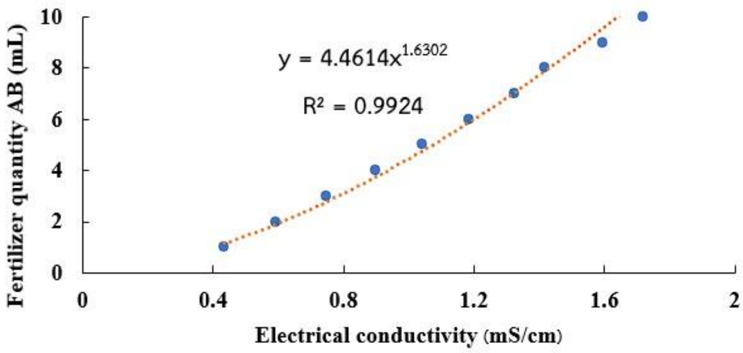


Figure 3. Estimation of linear exponentiation equations

$$\mathrm{EC}_{\mathrm{required}} = 4.4614\mathrm{EC}_{\mathrm{set}}^{1.6302} \quad (1)$$

Where $\mathrm{EC}_{\mathrm{required}}$ is required EC and $\mathrm{EC}_{\mathrm{set}}$ is range of value to be mixed.

Similarly, Figure 4 focuses on determining the precise timing for dispensing the necessary amount of liquid fertilizer. Accurate timing is essential to maintain nutrient consistency and prevent over- or under-fertilization. The estimated linear relationship between the timing and the fertilizer quantity was represented by the equation $y = 0.0519x - 0.0578$, also with an $R^2$ value of 0.9924. This indicates a high degree of accuracy and reliability in the model. The strong correlation values suggest that the developed models are reliable. Therefore, we can develop a new system equation to determine the amount of solution per unit time as shown in (2). This equation integrates the required EC and the volume to determine the operation time for the system to dispense the correct amount of AB solution, ensuring precise nutrient management in the system.

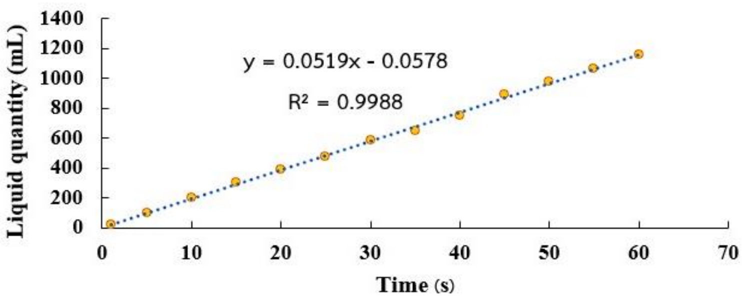


Figure 4. Relationship value for determining the time to release liquid volume

$$EC_{time} = (0.0519 \text{ x } EC_{required}) - 0.0578 \text{ x } V \quad (2)$$

Where $EC_{time}$ is pump operating time and V is volume of water that need to be mixed.

These findings provide a robust framework for optimizing nutrient solutions in soilless cultivation systems. By leveraging these mathematical models, we can precisely control both the quantity of fertilizer and the timing of its application, ensuring that plants receive consistent and optimal nutrition. Therefore, the equations obtained here will be used for programming to control the system.

## 2.3. Hardware system design

Figure 5 shows the components of the hardware used in this work. It consisted of a 100 L tank used for preparing and mixing the nutrient solution. There were four containers feed into the fertilizer system controller, which likely dispenses the appropriate amounts of each solution as needed. These containers included container A used for holds the first nutrient solution, container B used for holds the second nutrient solution, pH up container for raising the pH level of the solution and pH down container for lowering the pH level of the solution. There were two solenoid valves to controls the flow of water entering from a water source into the system, and another valve is used to controls the flow of the nutrient-rich, pH-adjusted water out to the plant system. An AC pump was used for transferring the nutrient solution between different tanks, a 12 V DC solenoid valve for controlling the flow of water into the mixing tank, an EC Sensor for measuring the EC of the nutrient solution, pH electrode (E201-C BNC) to measure the pH of the nutrient solution and a 2 L tank for measuring EC and pH after finishing mixing. In the design of the nutrient solution control system, a separate measurement tank was created to isolate the sensor probes from continuous immersion in the nutrient solution. This approach reduced wear on the sensors and increased their longevity. Chemicals used were: AB liquid fertilizer, dilute nitric acid and potassium hydroxide.

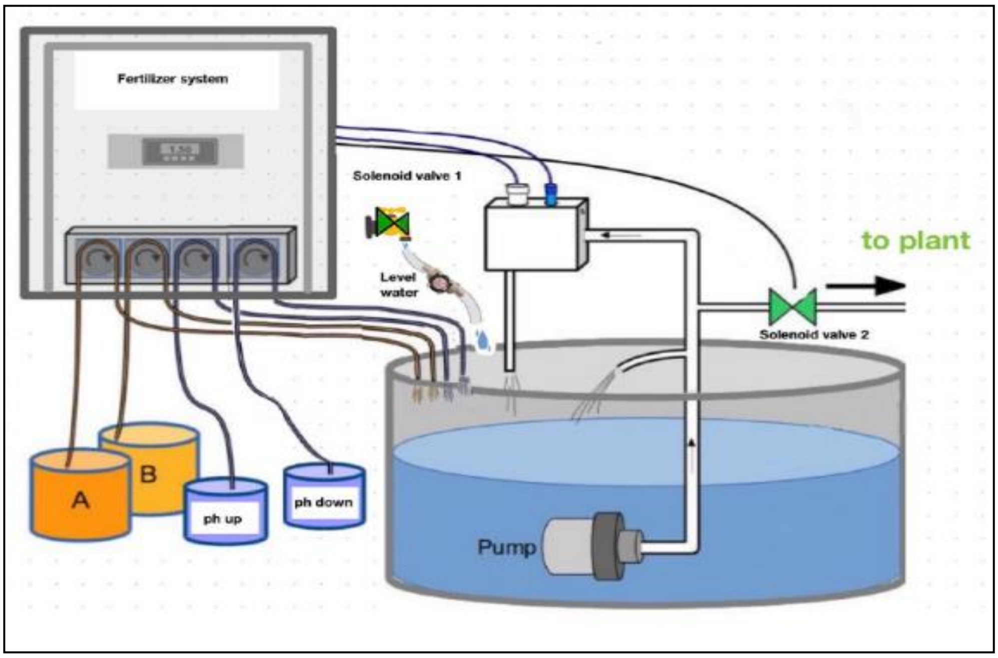


Figure 5. Hardware components and system design

## 2.4. Design of the control circuit

The nutrient controlling system is pictorially presented in Figure 6. The system consisted of an Arduino UNO R3 microcontroller serving as the central processing unit of the system, managing inputs from sensors and controlling outputs to various devices. There were two power supplies, the first was a switch power supply which provided a stable power source for the entire system. The second was a YwRobot power supply used to deliver regulated power to the Arduino and other low-voltage components. A 8-channel relay module were used to control multiple high-power devices, such as pumps and solenoids, by acting as an interface between the low-power control signals from the Arduino and the high-power devices. An AC pump was used for transferring large volumes of nutrient solution and a 12 V DC Pump was employed for precise, small-scale liquid transfers, offering fine control over nutrient solution mixing and dispensing. It was controlled with a 12 V solenoid that was used for regulating the flow of water into the mixing tank. There were three sensor types: EC sensor, pH sensor and temperature sensor.

The working principle of proposed system is illustrated in Figure 7. To initiate the process, the desired EC and quantity for mixing. The system will then activate the solenoid to allow water to enter the mixing tank according to the specified quantity were selected. Utilizing the linear regression equation, the system calculated the appropriate mixing ratio. This calculation determined the pump operation time required to release the solution into the mixing tank, where the agitation pump would then mix the solution thoroughly. Subsequently, the solution was pumped into the measuring tank to read the electrical conductivity, pH value, and temperature. Once the desired values were achieved, the system ceased operation, and the solution was ready for dispensing. This automated approach ensured precision and efficiency in preparing nutrient solutions tailored to requirements.

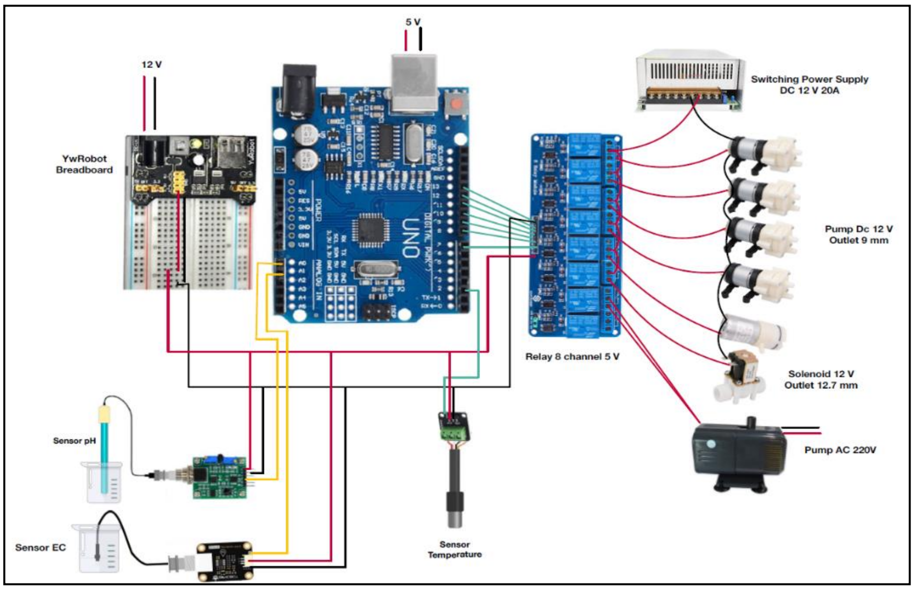


Figure 6. Schematic of control circuit design

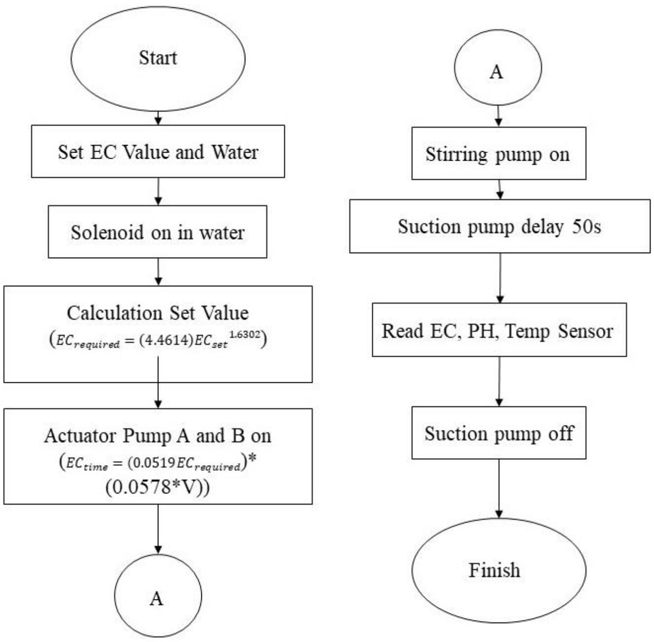


Figure 7. Flowchart of nutrient controlling process

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

This experiment aimed to evaluate system performance using a linear regression equation to control the nutrient solution. The system's effectiveness was evaluated through a series of experiments designed to validate mathematical model-based equations as shown in Figure 8. Tests were conducted at various desired EC levels, including 1.5, 1.7, 1.8, 1.9, 2.1, and 2.3 mS/cm, which represented the optimal values for most plant growth. The experiments were carried out with mixing volumes of 10 L and 50 L. Each value was tested three times to ensure consistency. During each test, we recorded the deviation in conductivity (referred to as the "difference value"), the percentage error (%error), the time required for the system to dispense AB liquid fertilizer into the mixing tank, and pH levels, to monitor trends in pH as conductivity varies.

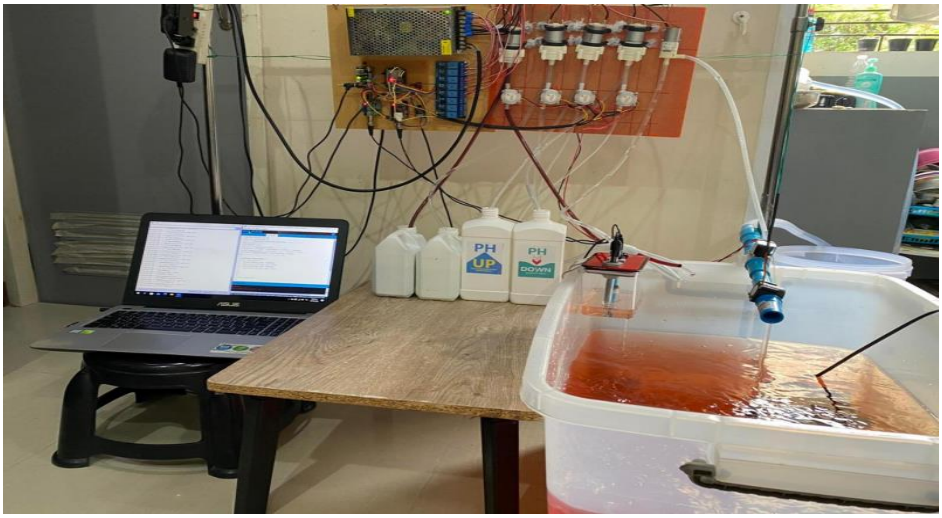


Figure 8. Nutrient controlling system performance testing

Based on the results for the nutrient controlling system, accuracy of the controlling system was calculated by comparing the value of EC measured value with set point. The calculation of error data of the nutrient controlling system of 10 L and 50 L are given in Tables 1 and 2, respectively. The results indicate that the system could achieve the desired EC using a proposed linear regression equation. For mixing volumes of 10 L, the maximum error was 1.75% or accuracy was 98.25% and the average error was 0.95% or accuracy was 99.15%. Mixing volumes of 50 L had the highest value of 2.89% or accuracy was 97.11% with the average error of 2.08% or accuracy was 97.92%. Additionally, it can be seen that the pH levels remained stable across all tests, indicating that changes in EC did not significantly affect pH, suggesting that pH adjustments were not necessary, as the values remained within acceptable limits. These findings demonstrated that the system could effectively control EC across a range of mixing volumes while maintaining consistent pH levels.

This study demonstrates a design for using linear regression models to manage the mixing of nutrient solutions. The results have been swown that it can use for developing a dependable and efficient nutrient mixing system suitable for different volumes and conductivity requirements. Table 3 provides a comparative analysis of various nutrient control methods employed in hydroponic farming, with a particular focus on their effectiveness in managing critical parameters such as pH, EC, and nutrient levels. The integration of IoT with the KNN algorithm, demonstrated a notable accuracy of 93.33% in nutrient level control [18], emphasizing the efficacy of combining real-time data acquisition with machine learning for precise nutrient management. In contrast, the IoT and Bayesian network model, monitored a broader range of parameters including light intensity, pH, EC, water temperature, and relative humidity but achieved a lower accuracy of 84.53% [19]. This outcome suggests that the increased complexity of managing multiple variables may introduce variability and reduce overall system accuracy. Fuzzy logic showed impressive accuracy, achieving 97.4% in pH control, which underscores its ability to handle uncertainties and maintain stable pH levels [22]. Meanwhile, CNNs performed exceptionally well, with accuracies of 96.65% for overall healthy control and 99.92% for pH control [26], illustrating their proficiency in analyzing complex patterns and making precise adjustments.

Linear regression methods displayed varying levels of effectiveness. For pH control, linear regression achieved an accuracy of 94.84% [28], indicating its reliability when relationships between variables are roughly linear. However, when applied to both EC and pH control [29], the accuracy for EC management was lower at 80.8%, whereas pH control maintained a robust accuracy of 95%, suggesting limitations in managing EC due to possible non-linear interactions. In contrast, the optimized linear regression approach developed in this study significantly improved nutrient management accuracy, achieving 97.92% for EC control and a perfect 100% for pH monitoring. These findings demonstrate that with proper calibration and optimization, linear regression can match or even exceed the performance of more sophisticated models like neural networks and fuzzy logic, especially in the context of pH management. This study demonstrates that the optimized approach highlights the potential of linear regression as a cost-effective and efficient solution for nutrient management in hydroponic systems, offering a compelling balance between simplicity and high performance. Furthermore, this proposed method presents an alternative approach for effectively managing another essential parameter in plant cultivation.

Table 1. Test results of the nutrient solution mixing system at a volume of 10 L

| EC desired value (mS/cm) | EC measured value (mS/cm) | | | EC Difference value (mS/cm) | %Error | Time (s) | pH value |
|---|---|---|---|---|---|---|---|
| | 1st time | 2nd time | 3rd time | | | | |
| 1.5 | 1.51 | 1.53 | 1.49 | 0.01 | 0.66 | 4.426 | 6.6 |
| 1.7 | 1.69 | 1.7 | 1.65 | -0.02 | 1.17 | 5.441 | 6.6 |
| 1.9 | 1.85 | 1.89 | 1.86 | -0.03 | 1.75 | 6.534 | 6.6 |
| 2.1 | 2.06 | 2.12 | 2.09 | -0.01 | 0.47 | 7.703 | 6.6 |
| 2.3 | 2.29 | 2.31 | 2.25 | -0.01 | 0.72 | 8.943 | 6.6 |

Table 2. Test results of the nutrient solution mixing system at a volume of 50 L

| EC Desired value (mS/cm) | EC Measured value (mS/cm) | | | EC Difference value (mS/cm) | %Error | Time (s) | pH value |
|---|---|---|---|---|---|---|---|
| | 1st time | 2nd time | 3rd time | | | | |
| 1.5 | 1.45 | 1.45 | 1.48 | -0.04 | 2.66 | 22.364 | 6.6 |
| 1.7 | 1.62 | 1.67 | 1.68 | -0.04 | 2.54 | 27.439 | 6.6 |
| 1.9 | 1.85 | 1.87 | 1.92 | -0.02 | 1.05 | 32.905 | 6.6 |
| 2.1 | 2.03 | 2.06 | 2.13 | -0.02 | 1.26 | 38.747 | 6.6 |
| 2.3 | 2.17 | 2.25 | 2.28 | -0.06 | 2.89 | 44.951 | 6.6 |

Table 3. Comparison of nutrient control methods for hydroponic farming

| Reference no. | Nutrient control method | Control parameter | Average accuracy |
|---|---|---|---|
| [18] | IoT and KNN | Nutrition level | 93.33% |
| [19] | IoT and Bayesian network model | Monitoring of light intensity, pH, EC, water temperature, and relative humidity | 84.53% |
| [22] | Fuzzy logic | pH value | 97.4% |
| [26] | CNN | healthy control and pH value | healthy control=96.65%, pH=99.92% |
| [28] | Linear regression | pH value | 94.84% |
| [29] | Linear regression | EC and pH value | EC=80.8%, pH=5% |
| [30] | Linear regression | nutrient solutions | 92.42% |
| [31] | Linear regression | nutrient solutions | 87.84% |
| This work | Linear regression | EC and monitor pH value | EC=97.92%, pH=100% |

## 4. CONCLUSION

This study presents a simple and effective design for using linear regression models to manage the mixing of nutrient solutions in hydroponic cultivation. The experimental results show that the system can maintain the desired EC across various mixing volumes, with a maximum error rate of 1.75% for 10 L volumes and 2.89% for 50 L volumes. These error margins demonstrate the system's ability to consistently achieve target EC levels, validating the accuracy of the control equation utilized. The high correlation coefficient ($R^2$) of 0.9924 underscores a strong, reliable relationship between the volume of AB liquid fertilizer and the resultant electrical conductivity, affirming the system's precision. These findings lay the groundwork for developing a dependable and efficient nutrient mixing system suitable for different volumes and conductivity requirements. Future work could explore the integration of real-time sensor feedback to enable dynamic adjustments, further enhancing the system's precision and adaptability to varying conditions.

## ACKNOWLEDGEMENTS

We would like to thank the project Total Innovation Management Enterprise (TIME) from National Science and Technology Development Agency (NSTDA), Thailand and Faculty of Engineering, Mahasarakham University, Thailand for the financial supported. We also thank All Information Technologies Co., Ltd., Thailand for equipment for testing.

## REFERENCES

[1] A. Fussy and J. Papenbrock, "An overview of soil and soilless cultivation techniques—chances, challenges and the neglected question of sustainability," *Plants*, vol. 11, no. 9, p. 1153, Apr. 2022, doi: 10.3390/plants11091153.

[2] R. S. Velazquez-Gonzalez, A. L. Garcia-Garcia, E. Ventura-Zapata, J. D. O. Barceinas-Sanchez, and J. C. Sosa-Savedra, "A review on hydroponics and the technologies associated for medium- and small-scale operations," *Agriculture*, vol. 12, no. 5, p. 646, Apr. 2022, doi: 10.3390/agriculture12050646.

[3] J. A. Dela Vega, J. A. Gonzaga, and L. A. Gan Lim, "Fuzzy-based automated nutrient solution control for a hydroponic tower system," *IOP Conference Series: Materials Science and Engineering*, vol. 1109, no. 1, p. 012064, Mar. 2021, doi: 10.1088/1757-899X/1109/1/012064.

[4] G. Wheeler, "Nutrient management in hydroponic systems: achieving optimal plant growth," *Journal of Agricultural Science and Botany*, vol. 8, no. 2, p. 234, 2023.

[5] L. I. Trejo-téllez and F. C. Gómez-merino, *Nutrient solutions for hydroponic systems - a standard methodology for plant biological researches*. IntechOpen, 2012.

[6] K. Phuphanphet and W. Sa-Ngiamvibool, "Fertility control system and pH Value for hydroponics cultivation," *Engineering Access*, vol. 7, no. 1, pp. 23–29, 2021, doi: 10.14456/mijet.2021.4.

[7] A. Naveena, S. N. Saheb, R. Mamidi, and G. L. N. Murthy, "Automated hydroponic nutrient control system for smart agriculture," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 33, no. 2, pp. 839–846, Feb. 2024, doi: 10.11591/ijeecs.v33.i2.pp839-846.

[8] H. J. Muhasin, A. Y. Gheni, N. I. I. Tajuddin, N. A. Izni, Y. Y. Jusoh, and K. A. Aziz, "A systematic literature review for smart hydroponic system," *Bulletin of Electrical Engineering and Informatics (BEEI)*, vol. 13, no. 1, pp. 656–664, Feb. 2024, doi: 10.11591/eei.v13i1.4738.

[9] M. Z. Asy'ari, J. F. Chrysdi Aten, and D. Prasetyo, "Growth predictions of lettuce in hydroponic farm using autoregressive integrated moving average model," *Bulletin of Electrical Engineering and Informatics (BEEI)*, vol. 12, no. 6, pp. 3562–3570, Dec. 2023, doi: 10.11591/eei.v12i6.4820.

[10] R. Lakshmanan, M. Djama, S. K. Selvaperumal, and R. Abdulla, "Automated smart hydroponics system using internet of things," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 6, pp. 6389–6398, Dec. 2020, doi: 10.11591/IJECE.V10I6.PP6389-6398.

[11] Y. L. K. Macayana *et al.*, "Internet of things-based indoor smart hydroponics farm monitoring system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 13, no. 2, pp. 2326–2339, Apr. 2023, doi: 10.11591/ijece.v13i2.pp2326-2339.

[12] A. Abu Sneineh and A. A. A. Shabaneh, "Design of a smart hydroponics monitoring system using an ESP32 microcontroller and the Internet of Things," *MethodsX*, vol. 11, p. 102401, Dec. 2023, doi: 10.1016/j.mex.2023.102401.

[13] M. F. Saaid, A. I. M. Yassin, and N. M. Tahir, "Automated monitoring and controlling pH levels for hydroponics cultivation technique," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 18, no. 3, pp. 1236–1243, Jun. 2020, doi: 10.11591/ijeecs.v18.i3.pp1236-1243.

[14] O. M. Elhassan Ahmed, A. A. Osman, and S. D. Awadalkarim, "A design of an automated fertigation system using IoT," in *2018 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCCEEE)*, Aug. 2018, pp. 1–5, doi: 10.1109/ICCCEEE.2018.8515772.

[15] M. A. Danial Bin Azman, S. Amely Jumaat, M. A. Johar, and U. Saleh Abu Bakar, "Development of automated nutrient composition control for fertigation system using IoT application," in *2023 IEEE 3rd International Conference in Power Engineering Applications (ICPEA)*, Mar. 2023, pp. 179–184, doi: 10.1109/ICPEA56918.2023.10093152.

[16] A. Rofi'i *et al.*, "Development of an iot-based portable smart fertigation module for automatic plant cultivation," *IOP Conference Series: Earth and Environmental Science*, vol. 1338, no. 1, p. 012056, May 2024, doi: 10.1088/1755-1315/1338/1/012056.

[17] M. C. Untoro and F. R. Hidayah, "IoT-based hydroponic plant monitoring and control system to maintain plant fertility," *INTEK: Jurnal Penelitian*, vol. 9, no. 1, pp. 33–41, Apr. 2022, doi: 10.31963/intek.v9i1.3407.

[18] D. Adidrana and N. Surantha, "Hydroponic nutrient control system based on internet of things and K-nearest neighbors," in *2019 International Conference on Computer, Control, Informatics and its Applications (IC3INA)*, Oct. 2019, pp. 166–171, doi: 10.1109/IC3INA48034.2019.8949585.

[19] M. I. Alipio, A. E. M. Dela Cruz, J. D. A. Doria, and R. M. S. Fruto, "On the design of nutrient film technique hydroponics farm for smart agriculture," *Engineering in Agriculture, Environment and Food*, vol. 12, no. 3, pp. 315–324, Jul. 2019, doi: 10.1016/j.eaef.2019.02.008.

[20] C.-H. Chen, S.-Y. Jeng, and C.-J. Lin, "Fuzzy logic controller for automating electrical conductivity and pH in hydroponic cultivation," *Applied Sciences*, vol. 12, no. 1, p. 405, Dec. 2021, doi: 10.3390/app12010405.

[21] P. Atmaja and N. Surantha, "Smart hydroponic based on nutrient film technique and multistep fuzzy logic," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 3, pp. 3146–3157, Jun. 2022, doi: 10.11591/ijece.v12i3.pp3146-3157.

[22] H. Fakhrurroja, S. A. Mardhotillah, O. Mahendra, A. Munandar, M. I. Rizqyawan, and R. P. Pratama, "Automatic pH and humidity control system for hydroponics using fuzzy logic," in *2019 International Conference on Computer, Control, Informatics and its Applications: Emerging Trends in Big Data and Artificial Intelligence, IC3INA 2019*, Oct. 2019, pp. 156–161, doi: 10.1109/IC3INA48034.2019.8949590.

[23] S. Mashumah, M. Rivai, and A. N. Irfansyah, "Nutrient film technique based hydroponic system using fuzzy logic control," in *2018 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, Aug. 2018, pp. 387–390, doi: 10.1109/ISITIA.2018.8711201.

[24] M. Fuangthong and P. Pramokchon, "Automatic control of electrical conductivity and PH using fuzzy logic for hydroponics system," in *2018 International Conference on Digital Arts, Media and Technology (ICDAMT)*, Feb. 2018, pp. 65–70, doi: 10.1109/ICDAMT.2018.8376497.

[25] I. Agustian, B. I. Prayoga, H. Santosa, N. Daratha, and R. Faurina, "NFT hydroponic control using mamdani fuzzy inference system," *Journal of Robotics and Control (JRC)*, vol. 3, no. 3, pp. 374–385, May 2022, doi: 10.18196/jrc.v3i3.14714.

[26] Fitriani, Z. Zainuddin, and Syafaruddin, "Nutrition control system in nutrient film technique (NFT) hydroponics with convolutional neural network (CNN) Method," in *2022 2nd International Seminar on Machine Learning, Optimization, and Data Science (ISMODE)*, Dec. 2022, pp. 41–46, doi: 10.1109/ISMODE56940.2022.10180412.

[27] D. Adiputra *et al.*, "Water quality monitoring with regression-based PPM sensor for controlling hydroponic dissolved nutrient," *Jurnal Ilmiah Teknik Elektro Komputer dan Informatika (JITEKI)*, vol. 9, no. 2, pp. 298–306, 2023, doi: 10.26555/jiteki.v9i2.25915.

[28] H. Helmy, D. A. M. Janah, A. Nursyahid, M. N. Mara, T. A. Setyawan, and A. S. Nugroho, "Nutrient solution acidity control system on NFT-based hydroponic plants using multiple linear regression method," in *2020 7th International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE)*, Sep. 2020, pp. 272–276, doi: 10.1109/ICITACEE50144.2020.9239134.

[29] T. Kaewwiset and T. Yooyativong, "Electrical conductivity and pH adjusting system for hydroponics by using linear regression," in *2017 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Jun. 2017, pp. 761–764, doi: 10.1109/ECTICon.2017.8096350.

[30] Helmy *et al.*, "Multiple linear regression method used To control nutrient solution on hydroponic cultivation," *Journal of Engineering Science and Technology*, vol. 17, no. 5, pp. 3460–3474, 2022.

[31] A. Nursyahid, H. Helmy, A. I. Karimah, and T. A. Setiawan, "Nutrient film technique (NFT) hydroponic nutrition controlling system using linear regression method," *IOP Conference Series: Materials Science and Engineering*, vol. 1108, no. 1, p. 012033, Mar. 2021, doi: 10.1088/1757-899X/1108/1/012033.


## BIOGRAPHIES OF AUTHORS

**Sirinya Chaila** received her B.Eng. in Electrical Engineering from Mahasarakham University, Thailand in 2020. Since 2021 until now, she is graduate student of the Department of Electrical and Computer Engineering, Faculty of Engineering, Mahasarakham University, Thailand. Her research interests include automation control system, IoT, smart farming, precision agriculture, and renewable energy. She can be contacted at email: sirinya.chaila@gmail.com.

**Chaiyong Soemphol** received his B.Eng. in Electrical Engineering with second-class honors from Khon Kaen University, Thailand in 2011. He also received his Ph.D. in Electrical Engineering from Khon Kaen University, Thailand in 2017. Since 2018, he has been with the Department of Electrical Engineering, Faculty of Engineering, Mahasarakham University, Maha Sarakham, Thailand as a Lecturer. His research interests include compact microstrip devices, metamaterial applications for RF, microwave sensor, wireless power transfer systems, renewable energy, automation control system, IoT, and precision agriculture. He can be contacted at email: chaiyong.s@msu.ac.th.