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Evaluation of Nutrient Dosing Methods for Hydroponic Crop Cultivation

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Abstract

The application of control systems for hydroponic cultivation in greenhouses has developed rapidly, and one of them is the nutrient-dosing control system. Various nutrient dosing control systems, such as on/off, fuzzy logic, and K-NN, have been widely discussed by many researchers. Nevertheless, there has been limited discourse regarding the employed dosing methods, namely sensor-based nutrient dosing and nutrient dosing based on the nutritional dilution equation. The objective of this study was to assess the effectiveness and efficiency of three nutrient dosing methods that can be used in control systems: nutrient dosing based on nutrient dilution equations (method 1), sensor-based (method 2), and a mixed nutrient dosing method combining the two previous methods (method 3). This research begins by identifying several nutrient dosing methods that can be used in control systems. After that, the dosing methods were tested, and data analysis was carried out. Based on the three methods proposed in this study, method 3 has the best results with a mean absolute percentage error (MAPE) of 0.77% and a root mean square error (RMSE) of 4.3, respectively, in relation to the targeted concentration of the nutrient solution. Method 2 has slightly higher results, with a MAPE of 0.82% and an RMSE of 4.62. Method 1 has the worst results, with a MAPE of 13.42% and a RMSE of 74.98. However, if the desired target nutrient concentration is less than 300 ppm, method 2 is the most suitable option compared to the other methods.

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1. Introduction

Plants production has always been an issue in agriculture. The expansion of agricultural land for increased production in developing countries has been widely carried out. However, this approach has created new issues as deforestation has increased CO_2 emissions, which are harmful to the environment (Barbier, 2004). Precision agriculture is one solution for increasing food production while protecting the environment. Narrow land use in urban areas can allow various technologies, such as automation in precision farming, to optimize crop cultivation activities (Benke & Tomkins, 2017). In addition, automation technology for precision agriculture is also widely used in greenhouses with various cultivation techniques, such as hydroponics, aeroponics, etc. Greenhouses are used due to unmet climatic or environmental conditions. In closed and controlled room conditions, it greatly facilitates the application of automation technology in implementing precision agricultural

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applications to form the desired growing environment. Various automation technologies can be used, such as lighting, temperature, and nutrition (Ivan & Escobar, 2017).

The nutrition management system for hydroponic cultivation is divided into two control systems: the nutrient dosing control system and the fertigation control system. The nutrient dosing control system controls the nutrient concentration before it is applied to the plants. This control system allows plants to get the right concentration of nutrients so they can grow optimally. The fertigation control system controls the time of application and the volume of nutrients given to plants. This control system makes the plant get the right amount of nutrients at the right time according to the plant's needs. This nutrient control system is essential to developing greenhouse automation technology because it influences production costs and environmental factors. The price of nutrient solids, which is quite expensive in the market, and the provision of nutrients that must follow the needs of plants can be solved with control system technology. In addition, environmental issues regarding fertilizer residues caused by excessive nutrition can be overcome by using control system technology.

According to Ahn et al. (2021) and Christie (2014), there are two methods in the nutrient-dosing system for hydroponic plant cultivation. The first method uses a sensor to read concentrations and mix nutrients with fresh water to form a ready-to-use nutrient solution. The sensors are based on electrical conductivity (EC), whose value correlates with the nutrient concentration level. According to Ahn et al., (2021), the use of the EC sensor method causes the proportion of nutrient absorption to be known based on the nutrients absorbed periodically. In addition, this method can also eliminate two unknown variables: transpiration and variations in total nutrient absorption. The use of EC sensors also has advantages where several types of sensors can identify macronutrients and micronutrients such as nitrogen, potassium, calcium, and copper so that they can produce intelligent control systems and can produce quality nutrients according to plant needs (Domingues et al., 2012; Vardar et al., 2015).

The second method is the theoretical concept of using the general dilution equation in **equation (1)** to find the nutrients needed to produce a ready-to-use nutrient solution (Christie, 2014).

$$C_1 \times V_1 = C_2 \times V_2 \quad (1)$$

where: C_1 = total dissolved solid of nutrient solutions A and B (ppm), V_1 = volume of nutrient solutions A and B (L), C_2 = total dissolved solid of ready-to-use nutrient solution (ppm), V_2 = volume of ready-to-use nutrient solution (L). In this method, to mix nutrient concentrates with fresh water, it is necessary to initially ascertain the concentration value and volume of the existing solution in the mixing tank. Furthermore, knowing the beginning concentration of nutrient concentrates in the nutrient container. This enables the creation of the nutrient solution with the desired concentration.

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Both methods can be applied to control systems as nutrient dosing methods. Many studies have been conducted regarding nutritional dosing control systems. Most of the control systems used are based on EC sensor readings. However, there are still few dose control systems that utilize methods based on nutrient dilution equations. Yolanda et al. (2016), Untoro & Hidayah (2022), Herman & Surantha (2019), Sholihah et al. (2021), Gumilang et al. (2018), Wedashwara et al. (2021), Mashumah et al. (2018), and Musa et al. (2019) developed a nutrient dosing control system for hydroponic cultivation based on fuzzy logic with input from EC sensor readings and output in the form of the duration of the pump flame to enter nutrient concentrations into the mixing tank. Adidrana et al. (2022) developed a hydroponic nutrient control system based on K-NN using IoT technology. Suseno et al. (2019), Maulana et al. (2019), Eridani et al. (2017), and Athanuzul & Amirullah (2021) also created a hydroponic nutrient dosing control system with an on/off control system based on EC sensor readings. In addition, Eka et al. (2017) also developed a control system for hydroponic cultivation that controls nutrient concentration, pH, temperature, and nutrition volume.

Specific discussions about the two nutrient dosing methods have never been carried out. For example, this includes discussions related to the time efficiency of mixing nutrients to reach the expected target, the effectiveness of the mixing method to obtain an accurate solution concentration, as well as the selection of the suitable method within a specific concentration target range. Therefore, this research discusses the nutrient dosing method that can be applied in control systems. The purpose of this study was to determine the most effective and efficient method of dosing nutrients for hydroponic cultivation based on the target set point concentration of the desired nutrient solution.

2. Materials and methods

This research began in October 2022-March 2023 at the Siswadhi-Supardjo Field Laboratory, Bogor Agricultural Institute.

2.1 Tools and materials

The prototype of a nutrient dosing control system was used to evaluate some nutrient dosing methods. The prototype consists of some component shown in the tools and materials in **Table 1** and **2**.

The prototype nutrition dosing control system consists of one set of sensors and a sensor module with electrical conductivity (EC), connected directly via cable to the Raspberry Pi, which functions as the central control system. In addition, the Raspberry Pi is also connected directly to actuators such as a peristaltic pump, which operates to pump nutrient solutions into nutrient mixing tanks and mixing pumps for mixing nutrient solutions. The scheme of the control system can be seen in **Figure 1**.

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Table 1. Tools for nutrient dosing control system

Tools	Model	Manufacture	Specification
Electrical conductivity sensor	Type K 1.0	Atlas Scientific	Range 5–200.000 µS/cm and accuracy ± 2%
Single-board computer	Raspberry Pi 4 Model B	Raspberry Pi	4 GB SDRAM
LCD	7” Capacitive Touch Screen LCD Model C	Waveshare	Resolution: 1024 x 600 with HDMI
Relay module	Relay module 2 channel	Songle	Input voltage is 5V, and maximum loads are AC 250V/10A and DC 30V/10A
Peristaltic pump	DIY dosing pump	Intllab	Input voltage is 12V and flow rate 5–100 ml/min
Water pump	PS-128 BIT	Shimizu	Power: 300 watts, maximum discharge: 33 L/min
Pipe	PVC pipe	Wavin	Diameter ¾”
Nutrient container	Jerry can	-	Material is HDPE, and volume is 5L
Mixing tank	Water tank	Pinguin	Material from PE and volume = 450 L

Table 2. Materials for nutrient dosing

Materials	Specification
Fresh water	Groundwater with a TDS < 100 ppm
Nutrient solution A	TDS ≈ 200.000 ppm
Nutrient solution B	TDS ≈ 200.000 ppm

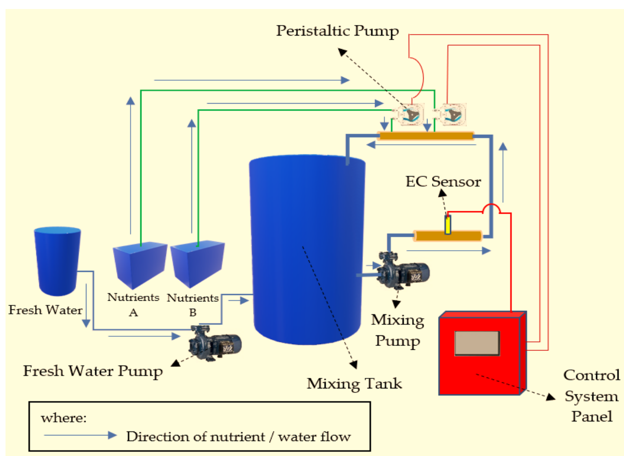

Figure 1. Schematic of the Nutrient Dosing Control System

2.2 Control system methods

This study used three nutrient dosing methods to dose nutrients into the mixing tank.

2.2.1 Method 1

Method 1 is a dosing control system based on the nutrient dilution equation mentioned in **equation (1)** previously. Based on the theory in **equation (1)**, **equation (2)** is obtained to calculate the volume of nutrients, which is the basis for the control system to determine the duration of the peristaltic pump to turn on to enter the nutrients into the mixing tank (Christie, 2014).

$$V_{concentrate} = \frac{(C_{target} - C_{now})\ x\ V_{max}}{C_{concentrate}\ x\ 2} \quad (2)$$

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where: $V_{concentrate}$ = volume of nutrients solution A or B that are put in the mixing tank (ml), C_{target} = desired nutrient concentration target (ppm), C_{now} = current nutrient concentration in the mixing tank (ppm), V_{max} = maximum volume of nutrients in the mixing tank (ml), $C_{concentrate}$ = concentration of nutrients solution A or B in the nutrient container (ppm)

The flow rate of the pump is obtained from the specification of the peristaltic pump used, which is 3.33 ml/s. The duration of the pump operation is determined by dividing the target volume by the pump flow rate, as shown in **equation (3)** below:

$$t = \frac{V_{concentrate}}{Q} \quad (3)$$

where: t = pump duration (s), $V_{concentrate}$ = volume of nutrients solution A or B that are put in the mixing tank (ml), Q = peristaltic pump flow rate (ml/s).

The mechanism of Method 1 can be seen in **Figure 2**.

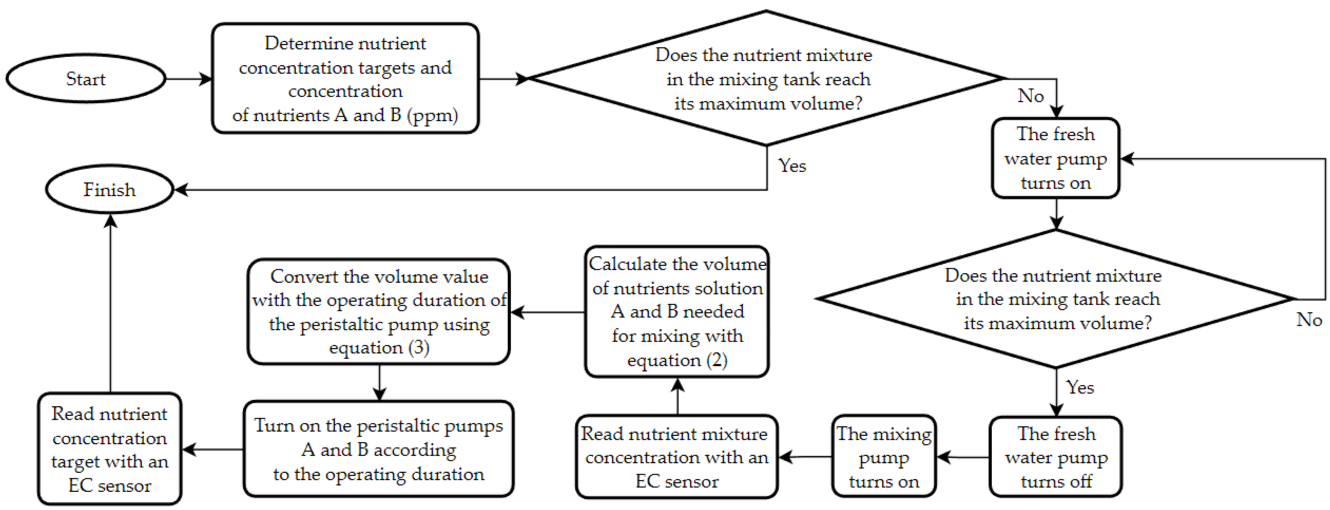

Figure 2. Flowchart of the mechanism dosing control system based on the nutrient dilution equation.

Method 1 begins with the preparation step by determining the desired nutrient concentration target. Then manually look at the volume of nutrient solution in the mixing tank. The mixing process is not carried out if the previously available nutrient solution is complete. Conversely, if the volume has decreased, the freshwater pump is turned on manually to fill the mixing tank. When the water condition in the mixing tank reaches a maximum volume of 450 l, the freshwater pump is turned off, and the nutrient mixing process is carried out automatically.

Nutrient mixing begins with turning on the mixing pump to circulate the water so that the EC sensor can read the initial concentration value of the fresh water in the mixing tank. Then the required volume of nutrients A and B is calculated by **equation (2)** and converted to the duration of the

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peristaltic pump to turn on and deliver nutrient concentrates into the mixing tank. The calculation of the duration value is done by **equation (3)**. Finally, to monitor the results of nutrient dosing, the EC sensor reads the concentration value of the nutrient solution to determine whether the dosing results have been effective and efficient.

2.2.2 Method 2

Method 2 in this nutrient-dosing control system is a nutrient-dosing control system based on sensor readings. The mechanism of this control system can be seen in **Figure 3**.

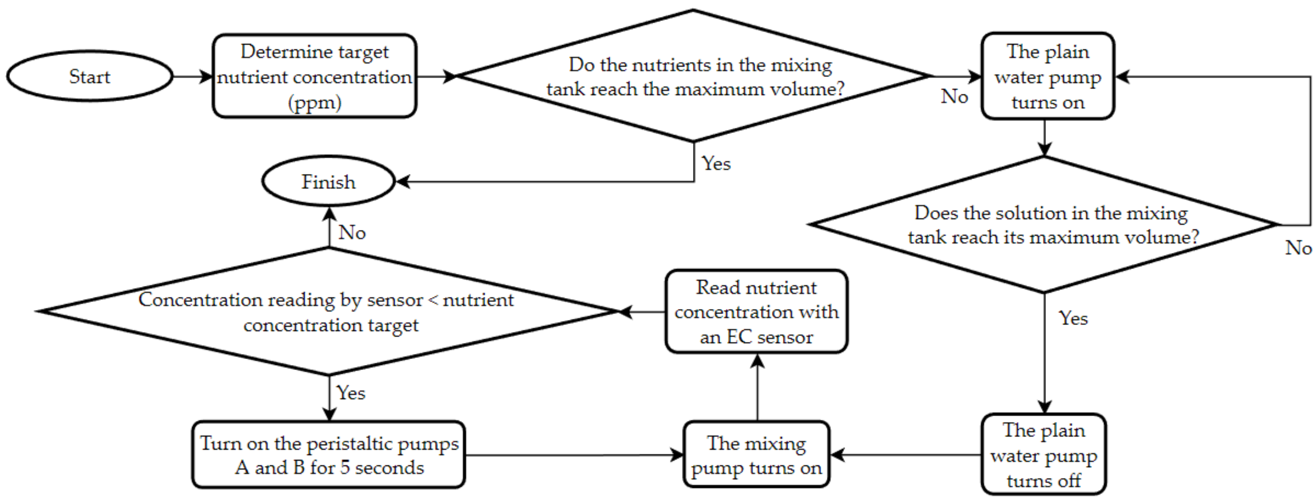

Figure 3. Flowchart of the mechanism of the dosing control system based on EC sensor readings.

In this second method, the preparation step is the same as in the first method. When the dosing process is ready, the control system turns on the mixing pump to circulate the water so that the EC sensor can read the initial concentration value of the fresh water in the mixing tank. If the concentration reading by the EC sensor is less than the desired target, the peristaltic pumps A and B will turn on for 5 s each. This step will repeat itself until the nutrient solution in the mixing tank reaches the desired target.

2.2.3 Method 3

Method 3 in this nutrient-dosing control system combines a nutrient dilution equation-based dosing control system with an EC sensor-based control system. The mechanism of this control system can be seen in **Figure 4**. In this third method, preparing to mix nutrients is the same as in the first and second methods. When the dosing process is ready, the control system will combine the nutrients based on the nutritional equation, as in the first method. The error obtained from the dosing results based on the nutrient dilution equation is then adjusted with a sensor-based dosing process to

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http://journal.ipb.ac.id/index.php/jtep
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minimize the error value. The nutrient dosing process is completed when the nutrient solution concentration reaches the desired target.

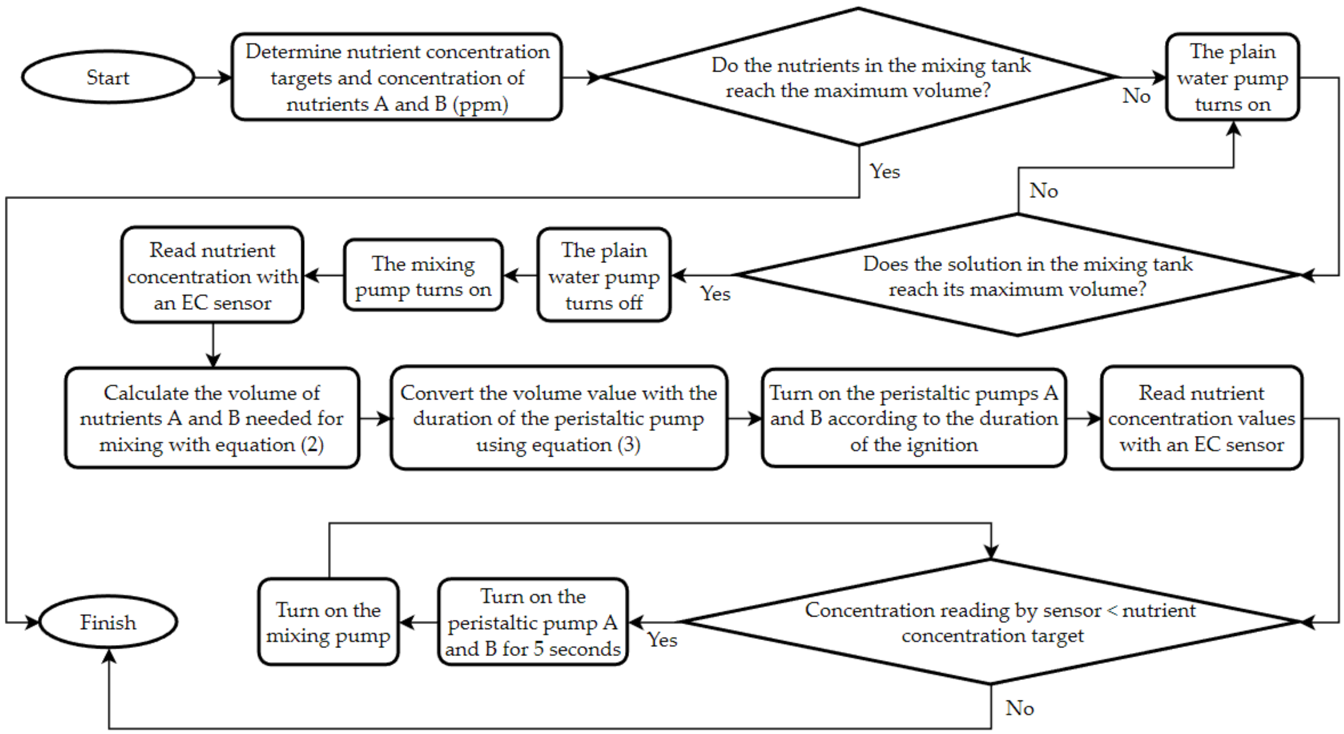

Figure 4. Flowchart of the mechanism of the dosing control system based on the nutrient dilution equation and EC sensor readings.

2.3 Control system testing

Testing the nutrient dosing methods is necessary to determine the effectiveness of the performance of the nutrient dosing methods that are applied in the control system. The test was carried out by knowing the error value of the control system on the desired target. The test was conducted from an initial freshwater concentration of around 100 ppm until it reached 1000 ppm. According to Rahmat (2015), it can be observed that plants typically exhibit a need for nutrients at a concentration of 250 ppm during their growth phase. The concentration value is anticipated to continue increasing, ultimately reaching a level of 1000 ppm as the system progresses towards the generating phase. There are two parameters for determining the error value from the results of this control system. The first is the mean absolute percentage error (MAPE), calculated by **equation (4)**, and the second is the root mean square error, which is calculated by **equation (5)** (Liu et al., 2021).

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{A_i - F_i}{A_i}\right| x100\% \quad (4)$$

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$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(A_i - F_i)^2}{n}} \tag{5}$$

where: n = number of observed data, A_i = target of nutrient solution concentration (ppm), F_i = concentration of the nutrient solution reached (ppm).

3. Results and discussion

The prototype of the nutrient dosing control system is used to test the three proposed methods of nutrient dosing. Two aspects can be reviewed in choosing the right control system for nutrient dosing in hydroponic cultivation. The first aspect is the efficiency of the mixing duration. The second aspect is the effectiveness of achieving the desired concentration of a nutrient solution.

3.1 Duration of nutrition mixing

The duration of mixing nutrients is the period the control system requires to mix nutrients A and B with fresh water until they reach the desired target concentration. The test was conducted with an initial freshwater concentration of around 100 ppm and a target concentration of 200 ppm. Subsequent tests were carried out in stages, with an increase in the target every 100 ppm until it reached 1000 ppm. The test results for the duration of mixing the nutrients can be seen in **Figure 5** and **6**.

Based on **Figure 5**, method 1 has the shortest duration compared to the other two methods. In contrast, method 3 has the most extended period compared to the other two methods, except for the target of 100 to 200 ppm. In addition, method 1 has a more stable average duration of mixing nutrients than other methods. It is because the method 1 is only influenced by the performance factor of the peristaltic pump in dosing nutrients into the mixing tank. The peristaltic pump performs excellently in the dosing process with a relatively small input volume and a discharge of around 1 ml/s (Nursyahid et al., 2021). It shows that method 1 is the most efficient in terms of time for mixing nutrients for plants in hydroponics. The unstable duration in methods B and C for each nutrient concentration target is caused by the dosing mechanism, which is carried out in stages, resulting in repeated sensor readings. The EC sensor issued by Atlas Scientific has an accuracy rate of 3.43% (Koparan et al., 2018). Therefore, the process results for one dosing stage give a concentration value with an error value of ± 3.43%. As the number of processes increases, the outcomes become more diverse, so the required duration will also differ.

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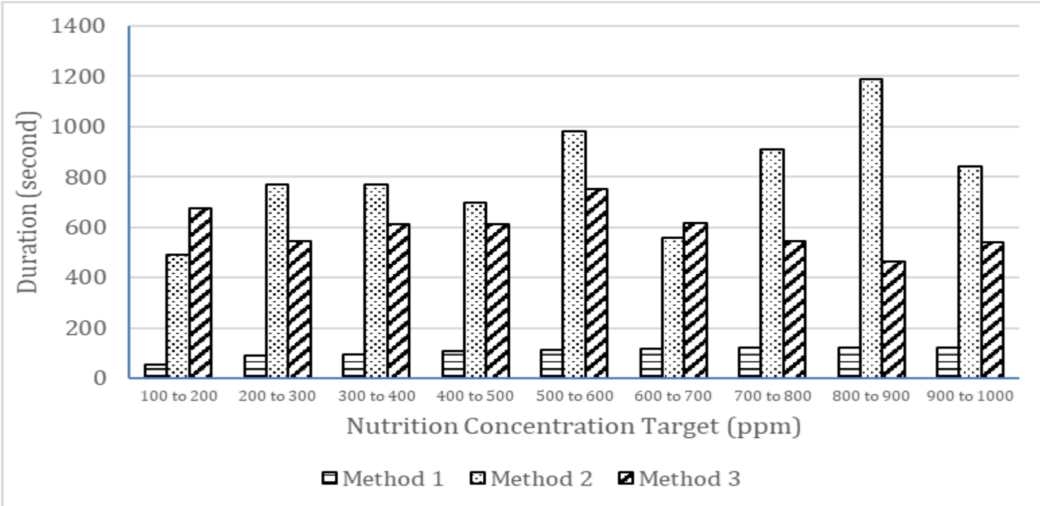

Figure 5. Duration of nutrient mixing in the three dosing methods

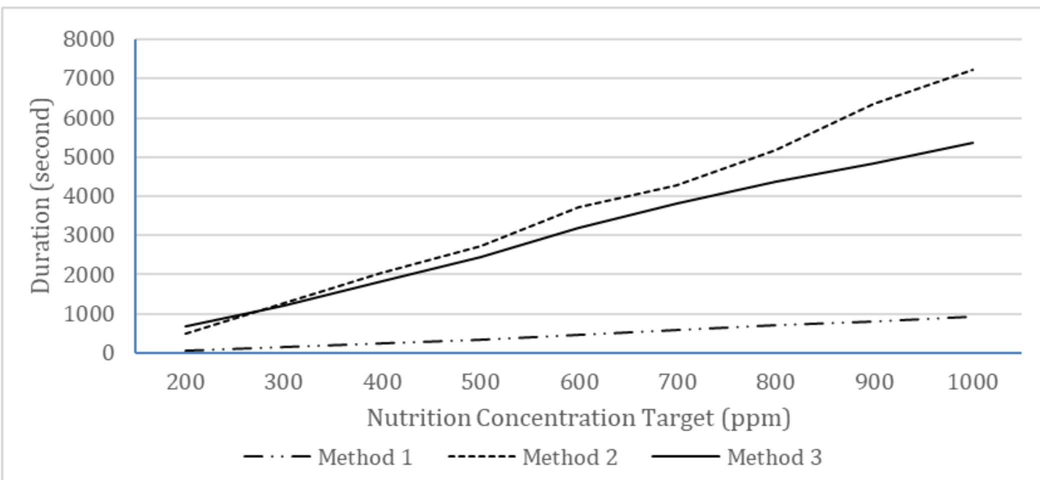

Figure 6. Accumulated nutrient mixing duration for the three dosing methods.

Figure 6 shows the accumulation time of nutrient mixing in the three proposed methods from a low concentration target (200 ppm) to a high concentration target (1000 ppm). Based on these results, method 1 takes up to 944 s to reach a concentration of 1000 ppm. In contrast, method 2 takes the longest time, namely 7210 s, to reach 1000 ppm. Method 1 requires a short time because when the control system is started, the dosing preparation process only begins with reading the value of the initial concentration of nutrients in the mixing tank with the EC sensor, then proceeding with mixing concentrates A and B by the peristaltic pump according to the duration calculated in the nutrient

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mixing equation. Method 2 takes the longest because the process of mixing the nutrients is carried out in stages according to the results of the sensor readings. Another factor that causes method 2 to take longer is that the mixing process will always be carried out first after the peristaltic pump has added concentrated nutrients A and B to the mixing tank. Method 3 requires a faster time than method 2, and it is because, at the beginning of the mixing process, the amount of nutrients put into the mixing tank is based on the calculated value of the nutrient mixing equation. So that the time to do the mixing process can be further trimmed, in **Figure 6**, it can also be seen that for targets below 300 ppm, method 2 has a shorter mixing duration than method 3. It shows that the nutrient dosing control system using the sensor reading method can be better used if the target concentration is below 300 ppm. Finding the same reference regarding the dosing mechanism used in this study is difficult, so the results cannot be compared directly. However, compared with the duration of dosing carried out by Untoro & Hidayah (2022) and Suseno et al. (2019) to increase the concentration of the nutrient solution every 100 ppm, this study required a much longer time. This study's dosing process prioritizes the accuracy of the results of mixing nutrients, so the pump used in this study has a small and constant discharge.

3.2 Effectiveness of nutrition mixing

The effectiveness of the nutrient dosing control system is seen in the error value generated by the control system against the expected target concentration. The test was conducted with an initial freshwater concentration of around 100 ppm and a target concentration of 200 ppm. Subsequent tests were carried out in stages, with an increase in the target every 100 ppm until it reached 1000 ppm. The test results on the effectiveness of mixing nutrients can be seen in **Figure 7**.

Based on the results in **Figure 7** and **8,** method 1 has a high error in the concentration value resulting from mixing the nutrients to the expected target concentration. This high error value can be caused by several factors, including the volume of water in the mixing tank that does not match the maximum volume, the difference in the concentration of nutrients A and B, and nutrient concentration values A and B that do not match the calculation variables. On the other hand, methods B and C have excellent accuracy values, where the average error value for each nutrient concentration target is below 5 ppm. In addition, the resulting error value is also relatively stable from low-concentration marks to high concentrations, unlike the case with method 1, which has a more significant error value when given a higher concentration target. It can happen because the calculation factor for the number of nutrients significantly affects the value of the concentration of the solution. So, if one of the calculation variables has a value that is not appropriate, the resulting error will be even greater if the variable being sought has a high value.

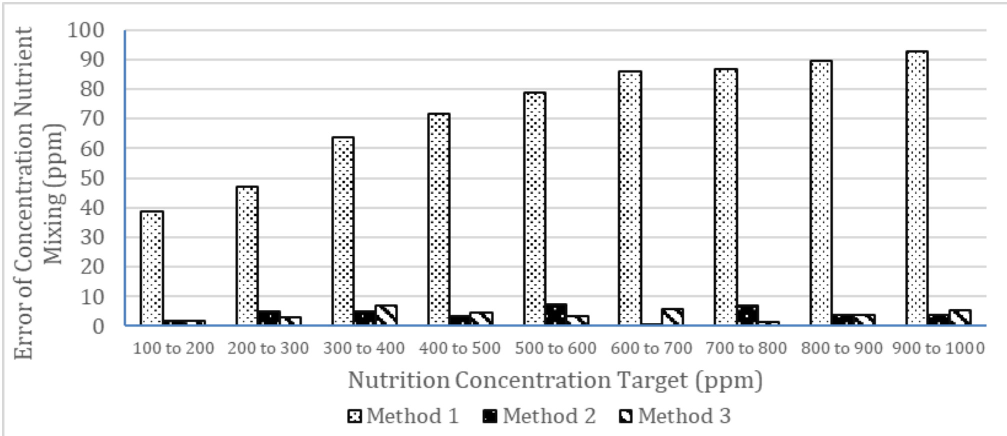

Figure 7. The error of nutrient mixing in the three dosing methods

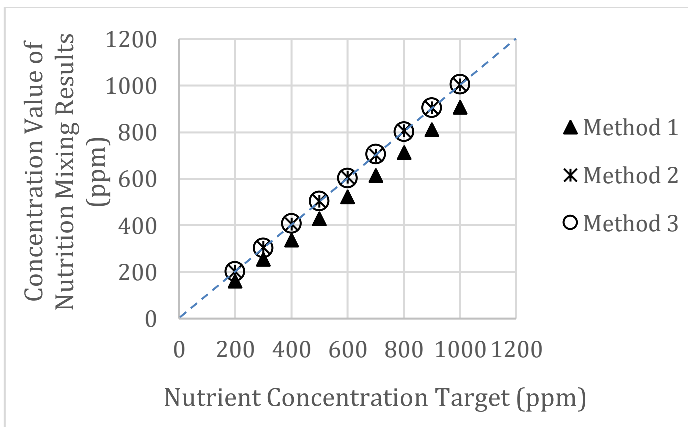

Figure 8. Accuracy of nutrient mixing in the three dosing methods

Table 3. RMSE and MAPE values from the test results of the three-dosing methods

	Method 1	Method 2	Method 3
RMSE	74.98	4.62	4.30
MAPE (%)	13.42	0.82	0.77

The error value was analyzed using the root mean square error and the mean absolute percentage error. Based on the results in Table 1, Method 3 has the best accuracy compared to other methods. These results indicate that in a nutrient dosing control system, the nutrient mixing equation method followed by sensor-based adjusting of nutrients until they reach the target concentration is very well used, especially for target nutrient concentrations above 300 ppm. Rahmat (2015) asserts that a significant proportion of plants grown through hydroponic cultivation necessitate nutrient levels between 250 to 1000 ppm for optimal growth. The nutrients employed are in the form of stock solutions A and B, which have been specifically formulated for specific plants. So, it can be concluded

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that method 3 is very suitable for mixing nutrients for various plant species using nutrient solutions A and B. Meanwhile, the nutrient mixing method based on sensor readings is perfect for targeting nutrient concentrations below 300 ppm. This method is most suitable when mixing nutrients in the form of single-element solutions, such as solutions of N, P, and K elements. These single-element solutions have a low concentration, which is below 300 ppm, before they are mixed into a complex nutrient solution (Frasetya et al., 2019). The percentage error values obtained in Methods 2 and 3 are much smaller than the results of a study conducted by Untoro & Hidayah (2022), which was 11.25%. These results indicate that method 1 is insufficient for dosing hydroponic nutrients. In contrast, methods 2 and 3 can be used for nutritional dosing, with the best results obtained in method 3.

4. Conclusion

There are three methods of nutrient dosing for hydroponic cultivation. Based on the test results, the nutrient dosing methods based on EC sensor readings (Method 2) perform best in carrying out nutrient dosing from 0 to 300 ppm. Method 2 is very efficient for mixing nutrients in the form of single elements. Moreover, the nutritional dosing method based on the nutrient dilution equation, followed by EC sensor readings (Method 3), performs best in carrying out nutrient dosing from 300 to 1000 ppm with the percentage error value was 0.77%. Method 3 is highly suitable for mixing nutrients in the form of stock solutions, like the commonly used nutrient solutions A and B for specific plants. The nutrient dosing method based on the nutrient dilution equation (Method 1) has a good duration performance that takes up to 944 second to reach a concentration of 1000 ppm., but this method has a high error value.

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