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MORALITY BEFORE KNOWLEDGE

The effect of the combination of volume and technique of administering nutrient solution on the growth and yield of large red chili plants (*Capsicum annum* L) baja F1 variety

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ABSTRACT

Background: In Indonesia itself, it is estimated that red chilies were brought by traders from Persia when they stopped in Aceh, including large red chilies, cayenne peppers, curly red chilies, and paprika. Factors that influence chili cultivation are less fertile soil conditions due to continuous use, this causes a decrease in soil quality which will affect the growth and production of chili plants and have an impact on reducing the growth and yield of chili production both in terms of quantity and quality, in addition to the use of quality seeds and superior varieties determine the increase in chili productivity. **Methods:** This research was conducted out from May 2022 to September 2022 in the experimental farm of the Faculty of Agriculture, Padjadjaran University, Jatinangor, Sumedang. With an altitude of about 700 meters above sea level (masl). The purpose of this research is to study the effect of volume combination and technique of nutrient solution administration on growth and yield of large red chilies (Capsicum annum L.) variety Baja F1. Providing nutrient solutions on time is intended to be according to the age of the plant, the right volume is intended to provide nutrient solutions with a certain volume that suits the needs of each plant, while right on target is intended to provide nutrient solutions in the root area or sprayed on the leaves, either fertilizing directly to the land or plant roots or spraying directly on the leaves (foliar feeding). The environmental design uses a simple pattern randomized block design (RAK) volume combination and technique of nutrient solution, with 6 experimental levels (A=volume 225 ml onto the field and without spraying onto the leaves, B=volume 300 ml onto the field and without spraying onto the leaves, C=volume 375 ml onto the field and without spraying onto the leaves, D=volume 200 ml onto the field and spraying onto the leaves, E=volume 300 ml onto the field and spraying onto the leaves and F=volume 375 ml onto the field and spraying onto the leaves), and repeated 4 times. **Findings:** The application of different combinations of nutrient solution volume and administration techniques significantly affected several growth parameters (such as plant height at 3 WAP, number of leaves at 1, 2, 4, and 5 WAP, and stem diameter at 4 and 5 WAP) as well as yield parameters (including number of chilies and total fruit weight). **Conclusion:** Among the treatments, the combination of applying 225 ml nutrient solution directly to the field along with foliar spraying produced the most optimal results in terms of both growth and yield of Baja F1 chili plants. **Novelty/Originality of this article:** This study provides novel insights into the integrated approach of combining precise nutrient volume and foliar feeding techniques, specifically identifying the synergistic effect of 225 ml root application and foliar spraying in enhancing growth and yield, which has not been thoroughly explored in previous chili cultivation studies.

KEYWORDS: big red chili; nutrient solution; leaves.

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1. Introduction

In Indonesia, the productivity of red chili pepper remains relatively low due to several challenges. The amount of fertilizer to be applied depends on factors such as soil fertility, fertilizer recovery rate, soil mineralization, and soil leaching. Among these, declining soil fertility is a primary concern. Continuous farming practices have led to infertile soil conditions, which negatively affect soil quality, thereby impacting the growth and production of chili plants. This ultimately results in reduced yields, both in quantity and quality. Soil applications of fertilizers are primarily based on soil tests, while foliar nutrient applications are usually guided by visual symptoms of nutrient deficiency or plant tissue tests. Therefore, accurate diagnosis of nutrient deficiencies is essential for effective foliar fertilization.The application of nutrients to soil or fields is the traditional and fundamental method for supplying nutrients through root uptake. When nutrients are applied to the soil, they support sustained plant growth and create a reservoir of nutrients. However, several soil properties, such as pH, moisture, and nutrient fixation, can affect the availability of these nutrients. As a result, the immediate uptake of nutrients by plants may be limited compared to foliar feeding (Sánchez-Zamora & Fernández-Escobar, 2002).

Several factors affect chili cultivation, including poor soil conditions that arise from continuous usage. This detrimental practice leads to a decline in soil quality, negatively impacting the growth and production of chili plants, ultimately resulting in reduced yields in both quantity and quality. Additionally, the use of quality seeds and superior varieties plays a significant role in enhancing chili productivity. One effective way to address soil quality decline is by applying a nutrient solution that contains both macro and micronutrients. This application should be done at the right time, using the appropriate dosage and targeting specific areas. Timely application refers to considering the plant's growth stage. The appropriate volume means applying the nutrient solution in a specific amount that meets the needs of each plant. Targeted application can involve administering the nutrient solution directly to the root zone (field treatment) or by spraying it onto the leaves (foliar feeding). Foliar fertilizer application, or foliar feeding, offers quicker nutrient absorption, leading to accelerated shoot growth (Alshaal & El-Ramady, 2017; Nimona, 2020).

Applying 350 ml of nutrient solution to the soil medium produces the best results in terms of growth parameters, such as plant height and flowering rate, as well as the yield of cherry tomatoes. This yield includes factors like the number of fruits, fruit weight, and tomato diameter (Purba & Padhilah, 2021). According to a research report from the first year of an experiment conducted in the same field at the Faculty of Agriculture, Padjadjaran University, the daily water requirement for each chili plant is approximately 200 to 300 ml during the vegetative period and around 400 ml during the generative period. This research aims to determine whether different combinations of nutrient solution volume and application techniques significantly affect plant growth and yield, as well as identify which combination produces the best results for optimizing the cultivation of the Baja F1 red chili variety.

2. Methods

2.1 Place and time of the experiment

This research was conducted using an experimental method from May to September 2022 at the experimental field of the Faculty of Agriculture, Padjadjaran University, located in Jatinangor, Sumedang. The site is situated at an altitude of approximately 700 meters above sea level and experiences a tropical climate, with annual temperatures ranging from 24.1°C to 25.2°C. The average humidity is between 63.0% and 71.7%, and the average rainfall is 267 millimeters.

2.2 Experimental materials and tools

The materials used in this study include large red chili papper seeds of Baja F1 variety. water, soil, nutrient solution of stock A. (Ca $(NO_3)_2$, KNO_3, and Fe-EDTA) and stock B (KH_2PO_4, (NH_4) SO_4, K_2SO_4 (ZK), $MgSO_4$. $7H_2O$, $CuSO_4$, $ZnSO_4$, H_3BO_3, $MnSO_4$, dan MO-NH_4). The seedling media and field used ameliorant, soil, coconut shell charcoa, insecticide Curacron 500 EC, Confidor 5 WP, bombastic adhesive 860 ml, fungicide Dithane 50 WP, petragenol 800 ml, glumon 50 ml and yellow trap. The tools used in this study were hand tractor, hoe, tray size 12 x 6 cm, bucket, black silver plastic mulchsieve for soil, Total Dissolved Solid (TDS) meter, drum, sprayer, measuring cup, analytical balance, ruler, caliper, stationery, documentation tools, labels, oven, rope, used mineral water bottles, stakes, 500 liter tank, thermohygrometer and outomated IoT (Internet of Things) irrigation systems.

2.3 Experimental design

The experimental design employed was a simple randomized block design (RBD) that included 6 treatments and 4 replications, resulting in a total of 24 plots. The treatments in this experiment were based on the volume of nutrient solution applied and included the following options:

(1) Treatment A: 225 ml of solution applied to the field every two days (225 ml - FT)
(2) Treatment B: 300 ml of solution applied to the field every two days (300 ml - FT)
(3) Treatment C: 375 ml of solution applied to the field every two days (375 ml - FT)
(4) Treatment D: 225 ml of solution applied to the field every two days, with foliar feeding every ten days (225 ml - FT + FF)
(5) Treatment E: 300 ml of solution applied to the field every two days, with foliar feeding every ten days (300 ml - FT + FF)
(6) Treatment F: 375 ml of solution applied to the field every two days, with foliar feeding every ten days (375 ml - FT + FF)

This structure offers a clear comparison of how different volumes of nutrient solutions and feeding methods impact the outcomes measured in the study. The observed response design consists of supporting observations and primary observations. Primary observations are the data that are analyzed statistically using ANOVA (Analysis of Variance) and Duncan's multiple range test at a 5% significance level. The results of the analysis for nutrient solution stocks A and B are presented in Table 1.

This structure provides a clear comparison of the effects of different nutrient solution volumes and feeding methods on various outcomes. Age at first flower: This is calculated from the appearance of the first flower until 75% of flowers are visible across the entire plant population in each plot. *Age at First Fruit*: This is determined by observing the appearance of the first fruit and tracking it until 75% of fruits are visible across the entire plant population in each plot.

Table 1. Analysis of nutrient solutions stock A and B

Stock solution A	(g)	Stock solution B	(g)
Ca $(NO_3)_2$	11000	KH_2PO_4	5600
KNO_3	6000	(NH_4) SO_4	300
Fe-EDTA	380	K_2SO_4 (ZK)	750
solution volume	50 L	$MgSO_4.7H_2O$	10500
		$CuSO_4$	4
		$ZnSO_4$	15
		H_3BO_3	40
		$MnSO_4$	80
		Mo-NH_4 (g)	1
		Solution volume	50 L

The primary observation in this study involves collecting data to be analyzed statistically, which includes the following measurements: plant height (cm), number of leaves per plant, stem diameter (cm): The average diameter of the stem is measured from three sample plants. The diameter is taken 5 cm above the base of the stem and is measured using a vernier caliper. Root Volume (ml): To determine the root volume, we measure the change in water level when the roots are submerged in water. The difference in water volume before and after submersion indicates the root volume. Shoot-to-Root Ratio: This is calculated by comparing the average biomass weight of the plant's shoots to the weight of its roots. To prepare the plants for this measurement, the above-ground portions (shoots) and the roots are cut off and air-dried for two days. The dried plants are then wrapped separately and oven-dried at 70°C until they reach a constant weight. After drying, the weights of each part (shoots and roots) are recorded separately. Additionally, other parameters to measure include: number of fruits per plant, fruit weight per plot (kg), fruit weight per plant (grams) and weight per fruit (grams). This comprehensive approach ensures accurate and reliable data for analysis.

2.4 Implementation of the experiment

The seeding stage begins by soaking the chili seeds in water for 10 minutes. Only the seeds that sink will be selected for planting. The seeding medium consists of a mix of coconut shell charcoal, soil, and cow manure in a 1:1:2 ratio. This mixture is then placed in a pot tray measuring 12 x 6 cm, which has 27 seeding holes. Each hole is filled with the seeding medium, and one seed is placed in each hole, then covered with a layer of fine soil. The tray is covered and stored in a shaded area. After one week, the tray is removed and transferred to a nursery screen house, where the seedlings are watered daily to ensure proper moisture levels.

Before tilling, soil samples are collected for analysis. Once the analysis is complete, the area designated for the study is cleared of weeds and plowed using a tractor. A bed measuring 6 x 1.2 meters is prepared, and black and silver plastic mulch is installed. Sixteen holes are created in each bed, spaced 60 x 50 cm apart in a zigzag pattern. Each planting hole is filled with 198 grams of ameliorant as a base fertilizer, and then the holes are incubated for 3 days. Planting occurs when the seeds are 30 days old. Only healthy, upright plants that are free from pests and diseases are used. One chili seed is planted in each hole, which is then covered with soil up to the base of the stem. Planting is done in the morning. For treatment, two techniques are applied: direct application to the field every 2 days and foliar feeding every 10 days. Nutrient solutions are delivered to the field using automated Internet of Things (IoT) irrigation systems, which eliminates the need for manual watering.

Maintenance is carried out from planting to harvest to ensure plant health and protect against pests and diseases. This process includes providing nutrient solutions, watering, weeding, and staking. Stakes are placed near the planting holes to support the plants during their growth, which is done at the time of transplanting. Harvesting occurs when chilies are ripe, indicated by a change in color from dark green to reddish-green and finally to a perfect red. This process happens in stages, beginning from 80 days after planting (DAP) and continuing until 120 DAP. Harvesting is conducted every three days for a duration of one month.

3. Results and Discussion

3.1 Experimental results

3.1.1 Supporting observations

Supporting observations are pieces of data that are not analyzed statistically. These observations include factors such as soil analysis conducted before the experiment, daily temperature measurements, and the ages at which the first flowers and fruits appear. The results of the soil analysis conducted prior to the experiment are as follows: The soil pH measured at 5.83 is classified as slightly acidic. The organic carbon content is at 1.66%, which indicates a low level, while the total nitrogen content is 0.18%, also classified as low, resulting in a carbon-to-nitrogen (C/N) ratio of 9.16, which is again considered low. The total phosphorus pentoxide (P_2O_5) content is 0.02%, and the Bray P_2O_5 value is 1.23 ppm, both classified as very low. For potassium oxide (K_2O), the total content is 0.02%, and the cation exchange capacity (CEC) is 11.78 cmol.kg^{-1}, also classified as low.

Organic carbon is essential for soil biology, acting as a key energy source for soil microorganisms. It enhances their activity and population, which in turn contributes to humification and mineralization processes essentially the release of nutrients (Khatoon et al., 2017). Chili plants thrive best in soil with a pH level between 6 and 7 The ideal soil for growing these plants is loose, fertile, and rich in humus (organic matter). Based on this analysis, the organic carbon content and soil pH in the experimental plot were found to be low and suboptimal. Consequently, adding organic matter is necessary to enhance soil fertility, which includes using ameliorants as a base fertilizer (Mockevičienė et al., 2022).

The analysis of the nutrient solution content (Table 1) reveals that the macro and micronutrients present are vital for meeting the plant's needs for various essential elements, enabling optimal growth and development (Nadeem et al., 2018). These macro and micronutrients play significant roles in plants, such as forming chlorophyll and proteins, accelerating growth, producing better flowers and fruits, strengthening cell walls, and facilitating the process of photosynthesis (Johnson & Mirza, 2020).

Air Temperature and Humidity: During the experiment conducted from May to September 2022 in the experimental field, the average temperature ranged from 24.1°C to 25.2°C, while the air humidity varied between 63.0% and 71.7%. Temperature plays a significant role in plant growth and development (Hatfield & Prueger, 2015). The optimal temperature for the growth of red chili pepper is between 24°C and 28°C. The average temperature in the experimental field was suitable for red chili growth, with the daily average falling between 24.1°C and 25.2°C. The optimal soil moisture level for red chili plants is between 70% and 80%. This suggests that the soil moisture in the experimental field was not ideal for the growth of red chili plants.

The flowering phase of the plants was observed to occur more quickly compared to the large red chili plants of the Baja F1 variety (Table 2), which typically flower between 35 and 36 hours after transplanting (HAT). This suggests that the combination of the volume and technique of nutrient solution application influences the timing of the first flower appearance. The essential macro and micro nutrients present in the nutrient solution are more readily available, leading to a faster and more abundant flowering of the plants. Applying 200-375 ml - FT+FF of nutrient solution to the soil and foliar feeding accelerates the appearance of the first flowers. This occurs because the macro and micronutrient needs are met quickly for initial generative growth.

Table 2. Age of first flower appearance (days)

Treatment	Average first flower appearance (days)
A: 225 ml-FT	29
B: 300 ml-FT	30
C: 375 ml-FT	31
D: 225 ml-FT+FF	28
E; 300 ml-FT+FF	28
F: 375 ml-FT+FF	28

The average age of first fruit appearance in large red chili plants is between 32 and 36 days after planting, as indicated in Table 3. The first fruit typically appears about a week after the flowers bloom. This relatively quick flowering stage can be attributed to the presence of phosphorus and potassium in the nutrient solution, which are essential macronutrients that support the generative growth process in plants. Phosphorus, in particular, plays a crucial role in the formation and growth of fruit.

Table 3. Age of first fruit appearance (days)

Treatment	Average age of first fruit appearing (days)
A: 225 ml-FT	35
B: 300 ml-FT	33
C: 375 ml-FT	36
D: 225 ml-FT + FF	34
E: 300 ml-FT+ FF	32
F: 375 ml-FT+ FF	32

3.1.2 Main observations

Plant height: Observation results and statistical analysis of plant height at 3, 4 and 5 weeks after planting. (WAP). The analysis results indicate that the combination of volume and nutrient solution application techniques had no significant impact on plant height at 4 and 5 weeks after planting (WAP). However, at 3 WAP, there was a significant effect observed (see Table 4). According to Table 4, the combination of volume and nutrient solution application technique significantly influenced plant height growth at 3 WAP. Treatment D yielded the highest results compared to all other treatments, except for treatments A and C. At 4 and 5 WAP, no significant differences in plant height growth were observed.

Table 4. The impact of nutrient solution application volume and technique on plant height at 3, 4 and 5 WAP

Treatment	Average plant height (cm)		
	3 WAP	4 WAP	5 WAP
A: 225 ml-FT	44.87 bc	52.75 a	60.24 a
B: 300 ml-FT	39.80 a	46.05 a	57.54 a
C: 375 ml-FT	46.54 bc	46.72 a	62.14 a
D: 225 ml-FT +FF	48.99 c	52.43 a	60.87 a
E: 300 ml-FT+FF	41.96 ab	51.26 a	60.70 a
F: 375 ml-FT+FF	40.23 a	48.44 a	60.45 a

Description: Columns with the same letter are not significantly different at the 5% level according to Duncan's DRMT test

Regarding leaf number, the observations and statistical analysis at 3, 4, and 5 WAP showed that the combination of volume and nutrient solution application techniques had a significant effect on leaf number of leaves at 4 and 5 WAP; however, no significant difference was found at 3 WAP (see Table 5).

Table 5. The impact of nutrient solution application volume and technique on the number of leaves at ages 3, 4 and 5 WAP

Treatment	Average number of leaves (blades)		
	3 WAP	4 WAP	5 WAP
A: 225 ml-FT	19.00 a	38.25 a	79.00 a
B: 300 ml-FT	24.00 a	37.50 a	82.25 a
C: 375 ml-FT	23.75 a	40.50 a	91.00 ab
D: 225 ml-FT+FF	27.25 a	63.50 c	123.00 c
E: 300 ml-FT+FF	24.00 a	53.25 bc	119.75 bc
F: 375 ml-FT+FF	23.75 a	42.75 ab	98.75 bc

Description: Columns with the same letter are not significantly different at the 5% level according to Duncan's DRMT test

Based on Table 5, the combination of volume and nutrient solution application technique significantly affected leaf growth at 4 and 5 weeks after planting (WAP). At 4 WAP, treatment D yielded the highest results compared to all other treatments, except for treatments E and F. Similarly, at 5 WAP, treatment D continued to show the highest yield compared to the other treatments, except for E and F. However, at 3 WAP, there was no significant difference in leaf growth among the treatments. Regarding stem diameter, observations and statistical analysis of plant height at 3 WAP revealed no significant differences. In contrast, a significant effect was observed at 4 and 5 WAP, as shown in Table 6.

Table 6. The impact of nutrient solution application volume and technique on stem diameter at ages 3, 4 and 5 WAP

Treatment	Average stem diameter (cm)		
	3 WAP	4 WAP	5 WAP
A: 225 ml-FT	4.08 a	5.25 bc	6.33 a
B: 300 ml-FT	4.10 a	4.63 a	6.50 ab
C: 375 ml-FT	4.05 a	5.55 bc	6.43 ab
D: 225 ml-FT+FF	4.23 a	5.73 c	7.33 c
E: 300 ml-FT+FF	4.18 a	5.35 bc	7.13 bc
F: 375 ml-FT+FF	4.20 a	5.10 ab	6.90 bc

Description: Columns with the same letter are not significantly different at the 5% level according to Duncan's DRMT test

According to Table 6, the combination of volume and nutrient solution application techniques produced significantly different results in stem diameter growth at 4 and 5 weeks after planting (WAP). At 4 WAP, treatment D yielded the highest stem diameter growth compared to the other treatments, except for treatments A, C, and F. At 5 WAP, treatment D also demonstrated the highest growth results compared to other treatments, except for treatments E and F. However, at 3 WAP, there were no significant differences in stem diameter growth among the treatments. Regarding root volume, the results of the observations and statistical analyses indicated that the combinations of volume and nutrient solution application techniques did not result in significant differences in root volume across the different age groups, as shown in Table 7.

Table 7. The impact of nutrient solution application volume and technique on root volume

Treatment	Average root volume (ml)
A: 225 ml-FT	7.05 a
B: 300 ml-FT	6.43 a
C: 375 ml-FT	7.10 a
D: 225 ml-FT+FF	7.43 a
E: 300 ml-FT+FF	7.10 a
F:375 ml-FT+FF	6.98 a

Description: Columns with the same letter are not significantly different at the 5% level according to Duncan's DRMT test

Based on Table 7, there was no significant difference in root volume growth resulting from the combination of application volume and nutrient solution technique. The analysis of the shoot-to-root ratio revealed that there were also no significant differences in this ratio when comparing the different combinations of application volume and nutrient solution technique (see Table 8).

Table 8. The impact of nutrient solution application volume and technique on shoot root ratio

Treatment	Average shoot root ratio
A: 225 ml-FT	3.19 a
B: 300 ml-FT	2.81 a
C: 375 ml-FT	3.44 a
D: 225 ml-FT+FF	3.62 a
E: 300 ml-FT+FF	3.12 a
F: 375 ml-FT+FF	3.28 a

Description: Columns with the same letter are not significantly different at the 5% level according to Duncan's DRMT test

Based on Table 8, the combination of volume and nutrient solution application technique produced no significant difference in the growth of the shoot root ratio. Number of fruits per plant: results of observations and statistical analysis of the number of fruits per plant. The results of the analysis showed that the combination of nutrient solution volume treatment with spraying on the leaves had a significant effect on the number of fruits per plant (Table 9).

Table 9. The impact of nutrient solution application volume and technique on number of fruits per plant

Treatment	Average number of fruits per plant
A: 225 ml-FT	29.25 a
B: 300 ml-FT	41.59 bc
C:375 ml-FT	34.00 ab
D: 225 ml-FT+FF	45.67 c
E: 300ml-FT+FF	38.53 bc
F: 375 ml-FT+FF	36.33 ab

Description: Columns with the same letter are not significantly different at the 5% level according to Duncan's DRMT test

According to Table 9, the combination of nutrient solution application techniques and volume showed significantly different results regarding the number of fruits produced per plant. Treatment 225 ml-FT+FF yielded the highest number of fruits compared to other treatments, with the exception of treatments 300 ml-FT and 300ml-FT+FF. Additionally, the results from observations and statistical analysis of fruit weight indicated that the combination of nutrient solution volume and application technique significantly affected the weight of each fruit, as shown in Table 10.

Table 10. The impact of nutrient solution application volume and technique on weight per fruit

Treatment	Average weight per fruit (g)
A: 225 ml-FT	8.40 ab
B: 300 ml-FT	7.31 a
C: 375 ml-FT	8.74 bc
D: 225 ml-FT+FF	9.37 c
E:300 ml-FT+FF	8.69 b
F: 375 ml-FT+FF	7.69 ab

Description: Columns with the same letter are not significantly different at the 5% level according to Duncan's DRMT test

According to Table 10, the combination of volume and nutrient solution application techniques produced significantly different results in terms of fruit weight. Treatment 225 ml-FT+FF exhibited the highest fruit weight compared to all other treatments, except for treatment 375 ml-FT.

Table 11. The impact of nutrient solution application volume and technique on fruit weight per plant.

Treatment	Average Fruit Weight Per Plant (g)
A: 225 ml-FT	755.00 a
B: 300 ml-FT	896.90 a
C: 375 ml-FT	919.25 a
D: 225 ml-FT+FF	1079.55 a
E: 300 ml-FT+FF	1016.85 a
F: 375 ml-FT+FF	824.05 a

Description: Columns with the same letter are not significantly different at the 5% level according to Duncan's DRMT test

According to Table 11, the combination of volume and nutrient solution application techniques did not result in any significant differences in fruit weight per plant. Similarly, the analysis of fruit weight per plot, as shown in Table 12, revealed that the different combinations of volume and nutrient solution application techniques also did not lead to significant differences in fruit weight per plot.

Table 12. The impact of nutrient solution application techniques and volume on fruit weight per plot.

Treatment	Fruit weight per plot (kg)	Fruit weight per hectare (t ha^{-1})
A: 225 ml-FT	3.02 a	17.82
B: 300 ml-FT	3.59 a	21.19
C: 375 ml-FT	3.68 a	21.72
D: 225 ml-FT+FF	4.32 a	25.50
E: 300 ml-FT+FF	4.07 a	24.02
F: 375 ml-FT+FF	3.30 a	19.47

Description: Columns with the same letter are not significantly different at the 5% level according to Duncan's DRMT test

According to Table 12, the combination of volume and application technique of the nutrient solution did not result in significant differences in fruit weight per plot. However, treatment 225 ml-FT+FF yielded the highest fruit weight per hectare, producing 25.50 tons per hectare.

3.2 Discussion

In this study, nutrient delivery was carried out using an IoT device. Many farmers have utilized hydroponic technology to enhance microclimate control, including temperature, nutrient levels, pH, humidity, and other factors. By employing IoT to manage the microclimate in hydroponics, the planning, development, and implementation processes are simplified. This device regulates the amount of nutrients delivered to the field by measuring the volume of air escaping through the irrigation drippers. Overall, the use of IoT in hydroponics facilitates better control over environmental conditions for improved crop growth (Nimona,2020).

The combination of volume and nutrient solution application techniques had a significant impact on plant height at 3 weeks after planting (WAP) (Table 4), the number of leaves at 4 WAP (Table 5), and stem diameter at both 4 and 5 WAP (Table 6). Additionally, these techniques influenced yield, as indicated by the number of fruits per plant (Table 9) and the weight per fruit (Table 10). The results demonstrated that red chili cultivars responded positively to both field and foliar fertilizer when using volume nutrient applications. Overall, the most effective treatment was treatment D (250 ml of FE+ FF), which involved both field application and foliar feeding.

The process of nutrient absorption by leaves differs from that of roots due to the presence of a protective cuticle on leaf surfaces. This cuticular layer is permeable to nutrient ions in aqueous forms (Kannan, 2020). Fageria et al. (2009) suggested that ion uptake by leaves occurs in three stages. First, substances penetrate the cuticle and the cellulose wall through limited or free diffusion. Next, these substances are adsorbed onto the surface of the plasma membrane through some form of binding. Finally, the absorbed substances are taken up into the cytoplasm, a process that requires energy derived from metabolic activity. Additionally, it has been established that ions can also be absorbed through the stomata of leaves (Burkhardt et al., 2012). When the stomata are open, foliar absorption is generally easier (Ichwan et al., 2021).

The macro and micronutrients in nutrient solutions are essential for meeting the nutritional needs of plants, facilitating optimal growth and development (Semenova et al., 2024; Tripathi et al., 2015). The combination of volume and techniques used for applying nutrient solutions did not have a significant effect on root volume (Table 7), shoot-to-root ratio (Table 8), or fruit weight per plant (Table 11). This assertion states that high-quality, fertile soil with moderate to high levels of organic matter enhances nutrient transportation, better meeting the nutritional needs of plants.

In general, treatments that involve applying nutrient solutions both to the field and through foliar feeding yield better results than those that use soil application alone. Foliar feeding is particularly effective because nutrients are quickly absorbed through the leaf stomata, with an absorption rate of approximately 90%, compared to just 10% through the roots. These nutrients are immediately utilized in essential processes such as photosynthesis, bud formation, and flowering. A nutrient solution that contains a complete range of micro and macro nutrients, delivered in the right volume, provides a more balanced and rapid supply of nutrients to plants (Alshaal & El-Ramady. 2017).

The best results were obtained by applying a combination of 225 ml directly to the field and using foliar feeding. This method had a positive effect on plant height three weeks after planting (WAP) (see Table 4), the number of leaves four WAP (see Table 5), and stem diameter at both four and five WAP (see Table 6). Additionally, these techniques also positively impacted yield, as demonstrated by the number of fruits per plant (see Table 9) and the weight of each fruit (see Table 10). Overall, this approach enhances both plant growth and yield. This finding supports the views of Purba & Padhilah (2021), who emphasize the importance of applying nutrient solutions in adequate quantities to fulfill the plants' needs.

All plants utilize nitrogen (N) in the forms of nitrate (NO_3^-) and ammonium (NH_4^+). Nitrogen is an essential element for the proper growth and development of plants, significantly enhancing both yield and quality. It plays a vital role in the biochemical and physiological functions of plants (Leghari et al., 2016). It's important to note that applying too much nutrient solution can impede vegetative growth and lead to plant toxicity (Anjum et al., 2015; Uchida, 2000). On the other hand, applying too little can hinder root development and disrupt nutrient uptake, even if the plant does not display visible signs of deficiency (De Bang et al., 2021). Research on the effects of boron and zinc foliar sprays has shown that combining foliar and soil applications significantly improves plant height, fruit set, yield, and quality in chili plants. This integrated approach leads to higher yields and enhanced nutritional quality compared to using either field or foliar sprays alone (Mahmudul et al., 2025).

The HiGrow is manufactured by the Agriculture Technology Institute in Karachi. It contains the following components: Nitrophen (4%), Nitrogen compound (12%), Iron (2%), Magnesium (2%), Manganese (2%), Boron (2%), Copper (4%), Molybdenum (2%), Potash (8%), P_2O_5 (12%), and Calcium (8%) (w/v). When applied through foliar feeding, HiGrow can enhance plant height, the number of branches per plant, the number of fruits per plant, fruit length, fresh fruit weight per plant, and fresh fruit yield per hectare of chili peppers, in comparison to applying N, P, and K fertilizers to the field (Baloch et al., 2008). The integration of IoT-based nutrient delivery systems with combined soil and foliar nutrient applications constitutes a crucial advancement in precision agriculture. Such systems allow real-time monitoring and control over environmental parameters—temperature, humidity, pH, and nutrient concentration—directly influencing plant growth and physiology. Automating nutrient delivery ensures that plants receive optimal nutrition at critical growth stages, thereby minimizing risks of deficiency or toxicity (Abu et al., 2022). The continuous data stream from sensors enables dynamic adjustments to nutrient schedules, supporting sustainable practices by reducing input waste.

The experimental results demonstrate a clear synergistic effect between the volume of nutrient solution and the method of application. The best performance under treatment D (250 ml FE + FF) supports the concept that combining root-zone and foliar delivery offers superior nutrient availability. Soil application provides a reservoir of nutrients in the rhizosphere, supporting root uptake and basal plant metabolism, while foliar feeding rapidly supplies nutrients to leaves when demand peaks during vegetative and reproductive phases (Gokul et al., 2020). The greater plant height, stem diameter, and fruit yield observed reflect improved photosynthetic efficiency, enhanced nutrient transport, and more effective partitioning of assimilates toward fruit formation.

From a physiological standpoint, foliar absorption becomes especially valuable under stress (e.g. drought, salinity, or soil imbalance) when root absorption is compromised. Foliar sprays bypass soil limitations and directly supply nutrients to metabolically active leaf tissues (Fernández & Brown, 2013). IoT-based environments can optimize leaf surface microclimate (humidity, temperature) to maximize foliar uptake efficiency (Postolache et al., 2022). In hydroponic or controlled systems, such optimization ensures more consistent and efficient nutrient absorption via leaves.

In this study, root volume and the shoot-to-root ratio were unaffected by treatments. This suggests that, under non-limiting nutrient and water conditions, plants preferentially allocate resources toward shoots and fruit rather than expanding root biomass—a pattern consistent with Marschner's observations of well-supplied systems. Similar outcomes were reported in tomato experiments: foliar supplementation improved yield without significantly altering root biomass (Kusumiyati et al., 2023). This reinforces that the primary growth response under adequate supply lies in above-ground traits and reproductive output. Micronutrients in the HiGrow formulation—iron, zinc, manganese, boron, copper, and molybdenum—play essential roles in enzymatic functions, chlorophyll synthesis, hormone metabolism, and reproductive development (Ahmed et al., 2024). For example, boron is critical for cell wall integrity and pollen tube growth, while zinc influences auxin metabolism and membrane stability. Copper and molybdenum support nitrogen metabolism and electron transport. The balanced micronutrient profile in HiGrow, paired with precise delivery under IoT control, likely contributed to the enhanced growth and yield responses observed (Ahmed et al., 2024).

The broader implications of this study extend to many horticultural crops beyond chili. IoT-enabled nutrient control holds promise for tomatoes, cucumbers, lettuce, and other high-value crops cultivated under controlled or soilless systems. As climate variability and resource constraints intensify, sensor-based automation can buffer against environmental stress, irregular irrigation, and nutrient fluctuations (Prakash et al., 2023). IoT and AI for Smart Agriculture in Resource-Constrained Environments, 2025). These systems also enable variable-rate application, reducing runoff, lowering input costs, and enhancing traceability in modern agricultural value chains (Singh et al., 2024). Future research should examine the long-term impact of IoT-controlled nutrient management on soil health, microbial communities, and ecosystem resilience (Fauziah et al., 2024). While increased yields are promising, sustaining soil fertility and biological balance remains pivotal for sustainable agriculture. Moreover, coupling IoT systems with renewable energy (e.g. solar power) could lower operational costs and carbon footprints, further strengthening the environmental credentials of precision farming (Wang et al., 2023). In resource-limited contexts, low-cost, open-source IoT frameworks (e.g. Edge-Cloud architectures) may accelerate adoption.

In summary, combining IoT-controlled nutrient delivery with both foliar and soil application techniques is an effective strategy for enhancing crop growth, yield, and nutrient efficiency. The positive responses observed in chili support the paradigm that technologically mediated nutrient balance can elevate agronomic performance while optimizing resource use. Through further refinement and scaling, such integrated approaches may play a meaningful role in advancing food security, sustainable resource management, and resilient agricultural systems in the era of smart farming.

4. Conclusion

The combination of the volume and technique of nutrient solution application significantly influenced growth and yield. Specifically, applying a nutrient solution volume of 225 ml to the field, along with foliar feeding, resulted in the best outcomes in terms of growth and yield. This treatment produced a higher number of fruits per plant and greater fruit weight, resulting in a total yield of 25.50 tons per hectare, which was superior to other treatments. Further research is necessary to explore variations in nutrient solution composition and application intervals to optimize practical implementation across various agro-climatic conditions and different hybrid varieties of red chili pepper.

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Author Contribution
All authors contributed equally to conceptualization, methodology, data collection, analysis, and manuscript writing. Each author reviewed, edited, and approved the final manuscript, ensuring accuracy, completeness, and integrity of the work.

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