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Effect of Different Nutrient Solutions and Multiple Bio-Stimulant Dosages on Yield and Growth of *Capsicum Annuum* in Soilless System

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Abstract

This study evaluates the impact of two nutrient solutions (F1 and F2) and varying dosages of the plant bio-stimulant Atomes F.D.Inc. Bio Sciences PHP®, (D1 = 50 mL, D2 = 100 mL, D3 = 150 mL, and D0 = control) on the growth and yield of *Capsicum annuum* in a hydroponic system. The results demonstrate that F2 significantly enhanced overall plant growth and yield compared to F1, with notable increases in fruit count (25±10 vs. 24±9), average fruit width (8.31±1.02 cm vs. 8.03±1.00 cm), average fruit length (11.79±1.19 cm vs. 11.55±0.89 cm), and total yield weight (2.85±0.89 kg vs. 2.68±0.91 kg). Plants treated with D3 exhibited the highest yield, with a total fruit weight of 3.90 kg, compared to 1.69 kg in the control group (D0). D3-treated plants also produced an average of 37 fruits, while D0 produced only 13. Conversely, D0-treated plants resulted in larger individual fruit sizes, with an average fruit width of 8.98 cm and a length of 13.20 cm, compared to 7.89 cm and 10.91 cm in D3-treated plants. These findings underscore the importance of precise nutrient management and bio-stimulant applications in optimizing hydroponic bell pepper production. Future research should focus on long-term economic feasibility and large-scale implementation strategies.

Keywords: *Capsicum annuum*, hydroponics, nutrient solutions, bio-stimulants, soilless agriculture

1. Introduction

Capsicum annuum L., widely recognized as bell pepper, is a crop of global significance due to its high nutritional value and economic importance. In addition to its prominent role in culinary applications, bell peppers are rich in antioxidants and vitamins, offering numerous health benefits (Swamy, 2023; Kelley *et al.*, 2009). Global demand for *Capsicum annuum* has led to an expansion in its cultivation area, with a harvested area of 2.055 million hectares reported in 2021 (FAOSTAT, 2023). Hydroponics has emerged as an efficient and sustainable cultivation method, allowing precise control of nutrient supply, reduced water usage, and year-round production (Sardare & Admane, 2013). However, optimizing hydroponic systems for *Capsicum annuum* requires the integration of suitable nutrient solutions and bio-stimulants. Bio-stimulants, such as plant growth-promoting rhizobacteria (PGPR) and other natural extracts, enhance nutrient absorption, root biomass, and crop yield (Rouphael & Colla, 2020). Despite its advantages, hydroponics adoption in Lebanon faces barriers such as technical challenges and financial constraints (Tabet *et al*., 2020). This study investigates the effects of different nutrient formulations and bio-stimulant dosages on the growth and productivity of *Capsicum annuum*, providing actionable insights into optimizing hydroponic pepper cultivation.

2. Materials and Methods

2.1 Description of the Work

The experiment took place between April and August 2024 at the Lebanese University's Agricultural Research and Training Center (CRFA) in Ghazir, Keserwan District, situated 550 meters above sea level. The greenhouse covered 224 m² and contained 48 substrate bags, each planted with three *Capsicum annuum* seedlings. The plants underwent seven harvests, with the first on July 2, 2024, and the final on August 13, 2024.

2.2 Meteorological Data

According to an online resource (Timeanddate.com), the temperature during the production phases ranged from 15 to 34 degrees Celsius, with an average maximum humidity of 66 to 72%.

2.3 Variety of Bell Pepper, Type of Substrate and Bio-Stimulant

The experiment used Sweet Pepper Sultan F1, a bell pepper variety from the United States, for its robust development and significant green fruits. It was recommended to plant after the final frost in April, ensuring nighttime temperatures exceed 13 degrees Celsius. Three-plant coco peat bags were purchased from Hawa Agri, and BioSciences PHP®, a rhizobacterial-based bio-stimulant from Atomes F.D. Inc. Company, was used to promote root growth and overall plant growth.

2.4 Substrate Bags and Planting

The coco peat bags were submerged in water for over 24 hours to expand the substrate. After being removed, they were placed in a greenhouse to install an irrigation system, complete with spaghetti and main pipes, and bell pepper seedlings were planted in the bags.

2.5 Fertigation

The fertigation of *Capsicum annuum* was executed using a Dosatron at the irrigation station of the center, with drippers at a 12 l/h flow rate. Fertilizers were made independently and weighed using a precision balance. Fertilizers were mixed with consideration of element compatibility to prevent precipitation and ensure nutrient availability. One tank contained calcium nitrate and iron chelate, while the other housed phosphates and sulfates. The production cycle included two phases: vegetative development (0-6 weeks) and blooming and fruiting (6-16 weeks). The ingredients for the two fertilization recipes are listed in Table 1.

Table 1. Components of F1 and F2 nutrient recipes during the two phases of the production cycle in ppm

Components of fertilization formulas	**Phase I 0-6 weeks**		**Phase II 6 – 12+ weeks**	
	F1	**F2**	**F1**	**F2**
Nitrogen (N)	237.50	224.00	376.18	189.00
Phosphorus (P)	140.70	47.00	125.00	47.00
Potassium (K)	216.60	281.00	434.00	351.00
Calcium (Ca)	57.00	212.00	171.00	190.00
Magnesium (Mg)	39.72	65.00	75.85	60.00
Iron (Fe)	12.53	2.00	13.95	2.00
Manganese (Mn)	4.97	0.55	4.46	0.55
Zinc (Zn)	1.02	0.33	5.84	0.33
Boron (B)	2.44	0.28	2.20	0.28
Copper (Cu)	0.13	0.05	0.85	0.05
Molybdenum (Mo)	0.11	0.05	0.10	0.05

2.6 Bio-Stimulant

The bio-stimulant was administered in three doses: 50 mL, 100 mL, and 150 mL, applied to two bags using the same fertilization recipe within the same block. It was applied once a week for the first month and twice every two weeks for the rest of the experiment. The bio-stimulant was mixed in water and rested for 30 minutes before application. The solution was manually administered to the seedlings, ensuring uniform distribution of the bio-stimulant to each seedling.

2.7 Experimental Design

The experiment involved 48 bags divided into two groups based on fertilization recipes (F1 and F2) and dosages (D1, D2, D3, and D0). The setup followed a split-split plot design with three repetitions. Each block had two fertilization recipes and three dosages, with two bags acting as the control group (D0).

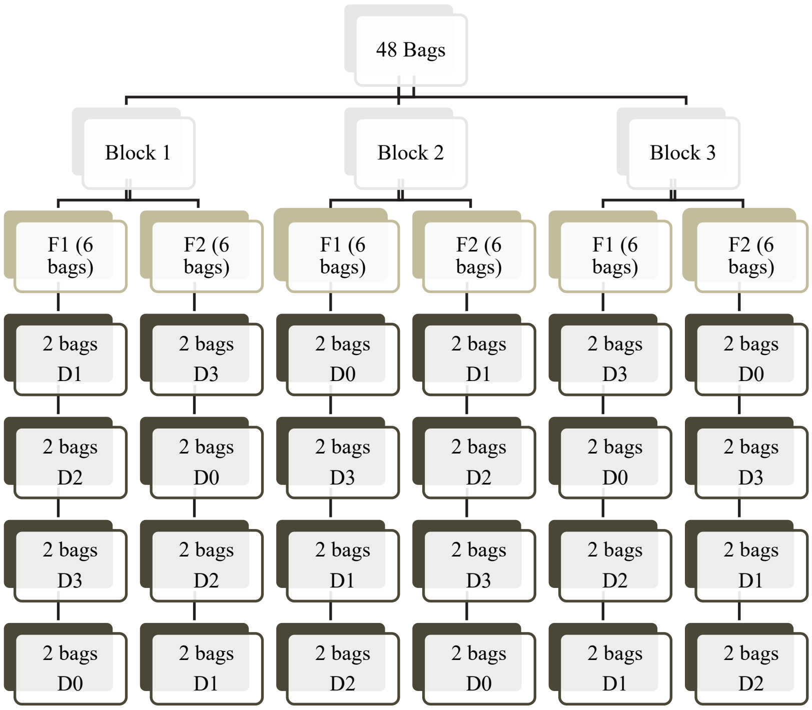
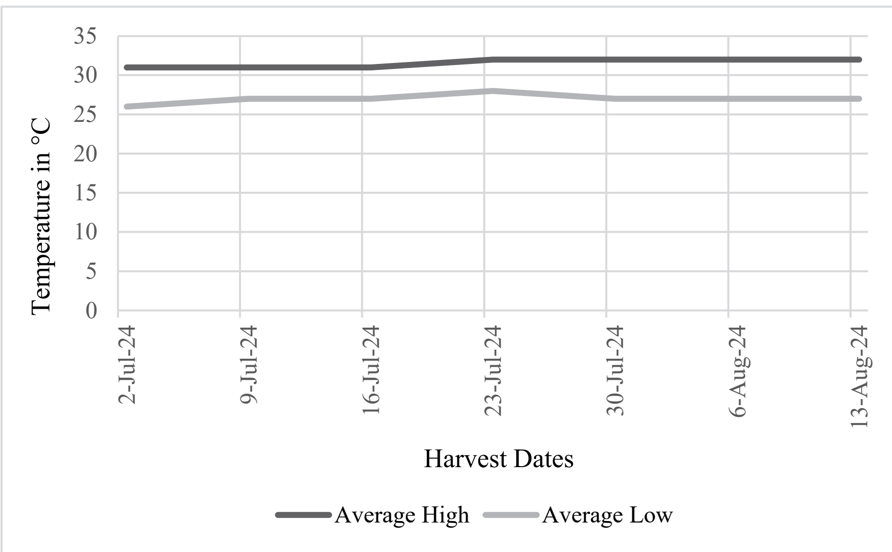


Figure 1.The experimental design used

The harvest period was also considered as a sub-factor. The temperature recorded from the first day of harvest to the last day is shown in the graph.



Graph 1. Forecast chart showing average high and low temperatures from the 1st harvest till the 7th harvest

Daily measurements of electrical conductivity (EC) and pH were taken throughout the experiment, as shown in table 2.

Table 2. Daily measurements of EC and pH

Fertilization recipe	Production phase	Ec	pH
F1	Phase I (0-6 weeks)	1.69	6.5
	Phase II (6-12+ weeks)	2.2	6.76
F2	Phase I (0-6 weeks)	2.33	6.54
	Phase II (6-12+ weeks)	2.49	6.99

2.8 Measured Parameters

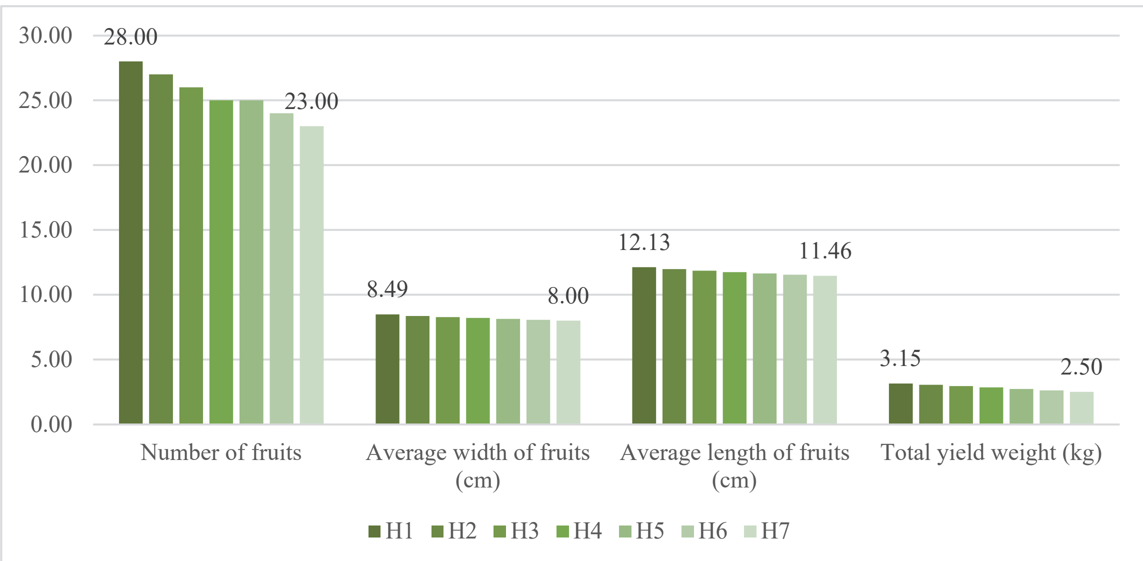
The parameters were categorized into two groups: those related to fruits at each harvest and those related to the plant at the end of the experiment. Data collection included number of fruits, average fruit length (cm) and width (cm), total yield weight (kg), dry root weight (g) and stem length (cm). Measurements were taken using a measuring tape, and yield and roots were weighed using a precision balance.

2.9 Statistical Analysis

The study used General Linear Model and Sigma stat software to analyze data. Three-way ANOVA with repeated measures was applied to compare the effects of Harvesting, Fertilization, and Dosage on Capsicum annuum fruits, considering a split-split plot design. The analysis included relative parameters like fruit number, relative average width (cm), relative average length (cm), and total yield weight (kg). Two-way RM ANOVA was used to compare fertilization and dosage effects on dry root weight (g) and stem length (cm). The Duncan test was used to differentiate significant differences between treatments at 0.05%.

3. Results and Discussion

3.1 Effect of Variations in Harvests on Parameters Taken at Each Harvest



Graph 2. Effect of variations in harvests on number of fruits, average width and average length of fruits (cm), and total yield weight (kg)

In graph 2, results showed that the first harvest H1 yielded the best results regarding number of fruits, average width and average length of fruits, and total yield weight.

Data analysis showed that harvesting had a significant effect on all parameters (P-values < 0.001). The average number of fruits dropped from 28 in the first harvest (H1) to 23 in the final. Increased temperatures in July and August most likely caused flower and fruit abortions, which is why this drop occurred. Erickson and Markhart (2001) and Díaz-Pérez (2010) both reported similar findings. Similarly, the average fruit width decreased from 8.49 cm (H1) to 8 cm during the last harvest, presumably due to high temperatures throughout the harvest time. Thuy and Kenji (2015) discovered that high temperatures greatly alter morphological features such as fruit width. Regarding the average length, it declined from 12.13 cm (H1) to 11.46 cm, most likely due to temperature fluctuations in July and August. Saha *et al*. (2010) found that high temperatures severely restrict fruit growth and length. The overall yield weight also reduced considerably, corresponding with research demonstrating that heat stress causes fruit physiological difficulties and flower and fruit abortion, resulting in losses (Olle, 2009; Angmo *et al*., 2022). Across all parameters, H1 produced the best results.

3.2 Effect of Variations in Nutrient Recipes on Parameters Taken at Each Harvest

In table 3, results showed that F2 produced the best results in terms of number of fruits, average width and average length of fruits, and total yield weight.

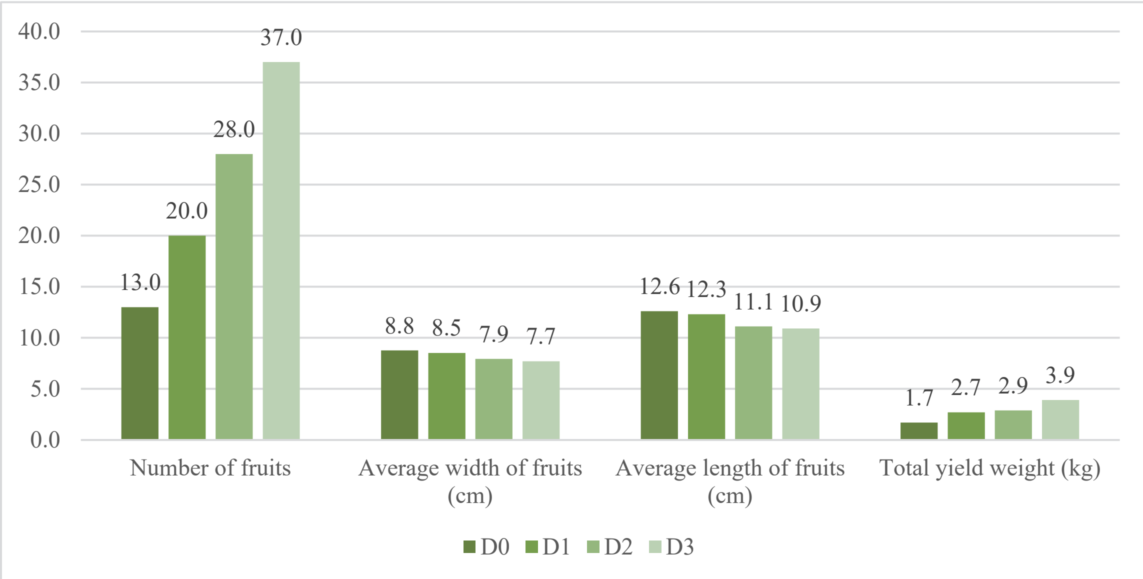
Table 3. Effect of variations in nutrient recipes on number of fruits, average width and average length of fruits (cm), and total yield weight (kg)

Mean ± Standard deviation of:	**Source of variation:**	
	F1	**F2**
Number of fruits	24±9	25±10
Average width of fruits (cm)	8.03±1.00	8.31±1.02
Average length of fruits (cm)	11.55±0.89	11.79±1.19
Total yield weight (kg)	2.68±0.91	2.85±0.89

The ANOVA findings showed that nutritional recipes had a substantial impact on all examined parameters (P-values < 0.001). F2 produced more fruits (25±10) than F1 (24±9), probably due to F1's lower potassium levels in Phase I (216.60 ppm < 281.00 ppm), which is crucial throughout the blooming and fruiting stages. Potassium has been shown to have a significant impact on plant growth, quality, and yield (Imas and Bansal, 1999; Lester *et al.,* 2006; El-Bassiony *et al*., 2010), with research showing that bell peppers' parameters are improved by higher potassium fertilization (Fawzy *et al*., 2005; Sabli and Zamri, 2012). A wider average width (8.31±1.02 cm) was also seen in F2 fruits compared to F1 fruits (8.03±1.00 cm), which may have been caused by F1's lower calcium levels in Phases I and II (57 ppm and 171 ppm < 212 ppm and 190 ppm, respectively). Fruit size and mass are impacted by calcium's effects on cell division and growth (Jing *et al*., 2024; Norton, 2013; Ali *et al*., 2021). The average fruit lengths of F2 were longer (11.79±1.19 cm compared to 11.55±0.89 cm), most likely because Phase I had higher potassium levels. Potassium has been shown to have significant effects on the length of fruits and plant development traits (Kusumiyati *et al.,* 2008), and it is essential for crop yield and quality (Pettigrew, 2008), and studies have confirmed its considerable impact on fruit length and plant development characteristics (Kusumiyati *et al.*, 2022; Somapala *et al.,* 2015). Finally, F2 had a larger overall yield weight (2.85±0.89 kg) than F1 (2.68±0.91 kg), which might be attributed to its lower nitrogen levels in Phases I and II (224.00 ppm and 189.00 ppm < 237.50 ppm and 376.18 ppm). According to research, too much nitrogen does not always boost yields or water use efficiency (Ayankojo, 2020), and a balanced nitrogen application is crucial for productivity (FAO, 2002; Aluko, 2015). Overall, F2 had better performance across all parameters.

3.3 Effect of Variations in Bio-Stimulant Dosages on Parameters Taken at Each Harvest:

In graph 3, results showed that D3 (150 ml) produced the best results in number of fruits and total yield weight. While D0 (control) outperformed the other options in average width and average length of fruits.



Graph 3. Effect of variations in bio-stimulant dosages on number of fruits, average width and average length of fruits (cm), and total yield weight (kg)

Data analysis showed that the bio-stimulant doses had significant effects on all tested parameters (P-values < 0.001). In terms of number of fruits, D3 (150 ml) produced the most, its efficiency in enhancing the fruit set, whereas the control group (D0) had the fewest. This is consistent with previous studies demonstrating the involvement of bio-stimulants' in improving blooming, growth, fruit set, and nutrient efficiency (Colla and Rouphael, 2015; Ricci *et al*., 2019). Ertani *et al*. (2015) found that bio-stimulants considerably boosted the fruit yield in *C. annuum*. Conversely, the control group (D0) had the largest average fruit width, with D3 generating the smallest fruits. Higher bio-stimulant doses may produce excessive vegetative growth, limiting the resources available for the fruit development and increasing shading under the canopy (Cmanneri, 2010). According to research, pruning can prevent excessive vegetative growth while also improving fruit size and quality. Similarly, the average fruit length was highest in the control group D0 (12.6 cm) and lowest in D3 (10.91 cm), indicating that vigorous plant development might result in smaller fruits (Kumar *et al*., 2019). However, PGPR has been shown to increase fruit size, including length and diameter, in many studies (Zapata-Sifuentes *et al.,* 2022; Camacho-Rodríguez *et al.,* 2022). In terms of total yield weight, D3 (150 ml) had the greatest yield (3.90 kg), whereas the control group (D0) had the lowest yield (1.69 kg), most likely owing to the larger number of fruits produced with appropriate bio-stimulant administration. This conclusion aligns with previous studies where a greater fruit count is a primary driver of higher production (Ombódi *et al*., 2019; Zapata-Sifuentes *et al*., 2022). Despite the limitations in fruit size parameters, D3 was shown to be the most effective dose for increasing fruit output.

3.4 Effects of Interactions Between Different Nutrient Recipes, Harvests, And Bio-Stimulant Dosages on Parameters Taken at Each Harvest

In table 4, the results show that the F2D3 yielded the best results in terms of the number of fruits and total yield weight, while F2D0 produced the greatest results regarding the average width and length of fruits.

Table 4. Effect of interactions between nutrient recipes and bio-stimulant dosages on number of fruits, average width and average length of fruits (cm), and total yield weight (kg)

Source of variation:	Mean ± Standard deviation			
	Number of fruits:	Average width of fruits (cm):	Average length of fruits (cm):	Total yield weight (kg):
F1D1	20.33±2.50	8.45±0.34	12.32±0.54	2.68±0.43
F1D2	27.19±3.12	7.69±0.24	10.87±0.28	2.80±0.39
F1D3	34.95±3.75	7.96±0.24	11.17±0.25	3.74±0.64
F1D0	13.24±2.34	8.01±1.90	11.86±1.22	1.52±0.24
F2D1	19.19±2.40	8.59±0.24	12.14±0.41	2.68±0.29
F2D2	28.33±2.94	7.77±0.22	10.91±0.25	2.90±0.32
F2D3	37.67±4.93	7.89±0.19	10.91±0.24	4.05±0.49
F2D0	13.57±2.06	8.98±1.78	13.20±1.32	1.79±0.32

The ANOVA table revealed that only the Recipe × Dosage Treatment interaction was significant for all assessed parameters. F2D3 (37.67±4.93) produced the most fruits, while F1D0 (control) had much lower fruit counts. This emphasizes the significance of coupling optimum nutrient formulations with bio-stimulant doses, as fertilizers alone are insufficient to maximize efficiency (Anton-Herrero *et al.,* 2023). These findings are in accordance with a study proving that bio-stimulant treatment increased fruit numbers and overall yield (Golian *et al.,* 2024). Regarding the average fruit width, F2D0 generated the largest average fruit width (8.98±1.78 cm), while F1D2 resulted in smaller fruits (7.69±0.24 cm). This may be linked to plant size and the balance of fruit load and photosynthetic resources (Raharris, 2023). Ding *et al*. (2017) highlighted the need of maintaining a sustainable crop load for consistent production and quality. However, the control group's greater width contradicts a previous study that PGPR treatment often improves fruit size (Zapata-Sifuentes *et al.,* 2022). For average fruit length, F2D0 yielded the longest fruits (13.20±1.32 cm), while F1D2 produced shorter fruits (10.87±0.28 cm). The decline in fruit size observed with greater bio-stimulant dosages might be attributed to resource competition caused by excessive fruit production (Cmanneri, 2010). A similar experiment on *C. annuum* found longer fruits in the control group with reduced fruit yield (Chaitra *et al.,* 2024). Finally, for the total yield weight, F2D3 had the largest yield (4.05±0.49 kg), while F1D0 had the lowest (1.52±0.24 kg). This is in accordance with studies confirming the efficacy of PGPR in increasing fruit yield and nutritional value (De Andrade *et al*., 2023; Ertani *et al.,* 2014; Pereira *et al.,* 2016). Across all parameters, other interactions showed minor but statistically insignificant differences. The interaction between the recipe and the dosage treatment had a significant effect on the fruit production parameters. F2D3 consistently outperformed in most measurements, whereas F2D0 excelled in fruit size. This emphasizes the significance of balancing fertilizer content and bio-stimulant treatments to improve hydroponic bell pepper development.

3.5 Effect of Variations in Nutrient Recipes on Parameters Taken at The End of the Experiment

In table 5, results showed that F2 outperformed F1 in both dry root weight and stem length.

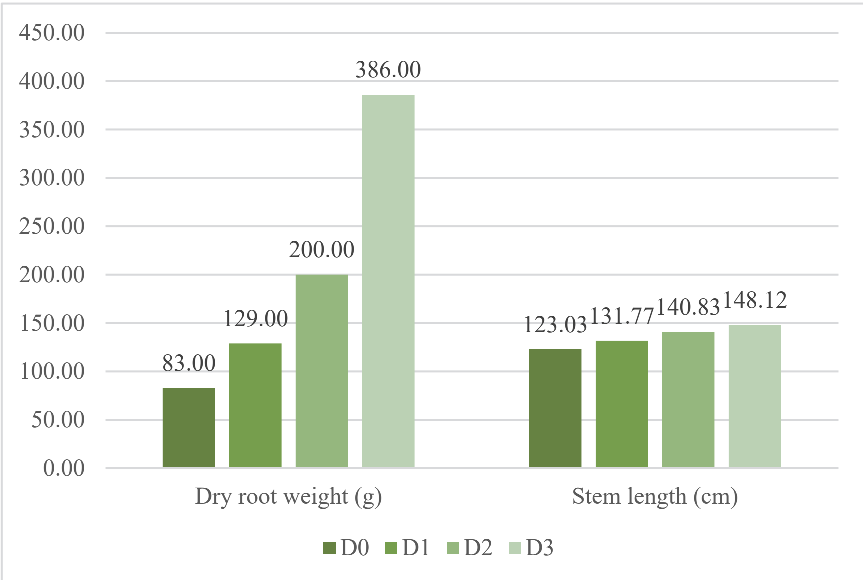
Table 5. Effect of variations in nutrient recipes on dry root weight (g) and stem length (cm)

Mean ± Standard deviation of:	Source of variation:	
	F1	F2
Dry root weight (g)	194.33±117.42	205.33±127.33
Stem length (cm)	135.08 ± 9.90	136.79±10.07

The ANOVA results revealed that the different nutrient recipes did not significantly influence the dry root weight and stem length (P-value > 0.05). Despite a lack of statistical significance, F2 performed slightly better than F1, with average dry root weights of 205.33±127.33 g compared to 194.33±117.42 g. Similar experiments on C. annuum L. found no significant influence of the NPK fertilizer on the root dry weight (Ichwan *et al*., 2023). For stem length, F2 had a small edge in stem length with no statistically significant effect, measuring 136.79±10.07 cm compared to 135.08±9.90 cm in F1. However, the lack of statistical significance might be attributed to nutritional imbalances or a high plant load, which could hinder stem development (Kaarsemaker, 2018). Furthermore, a study of increasing NPK levels in bell pepper development discovered no significant influence on stem length (Toungos, 2017). F2 had a marginal advantage in both parameters, although the differences were not statistically significant, emphasizing the necessity of balanced nutrient treatments and the possibility of bio-stimulants to improve plant growth.

3.6 Effect of Variations in Bio-Stimulant Dosages on Parameters Taken at The End of the Experiment

In graph 4, results showed that D3 outscored the other options in terms of dry root weight and stem length.



Graph 4. Effect of variations in bio-stimulant dosages on dry root weight (g) and stem length (cm)

The data analysis revealed a significant effect of bio-stimulant dosages on both dry root weight and stem length (P-value < 0.001). Among the treatments, D3 (150 ml) generated the highest dry root weight at 386.33 g, whereas D0, the control group, produced the lightest roots, averaging 83.33 g. This result can be related to the effect of Biosciences PHP in transferring helpful bacteria into the root zone (Atomes F.D. Inc., 2023). Such bacteria, particularly plant growth-promoting rhizobacterium (PGPR), have been found to change the root architecture, increasing the total surface area accessible for nutrient and water absorption, resulting in improved plant growth and health (Barnawal *et al.,* 2019). Grover *et al.* (2021) demonstrated that several PGPR species alter the root architecture by creating phytohormones, volatile organic compounds, and secondary metabolites, which improve the rhizosphere's nutrition exchange capacity. Similarly, D3 (150 ml) produced the longest stems, measuring 148.12 cm compared with 123.03 cm in the control group (D0). PGPR stimulates plant growth and development by secreting regulatory compounds into the rhizosphere (Nehra and Choudhary, 2015). Bai *et al*. (2007) found that bio-stimulants had a significant impact on plant height and other physical features. Furthermore, Mahmood (2017) found that the beneficial effects of bio-stimulants are proportional to their concentration, with higher concentrations resulting in increased plant height and leaf area. In every parameter, D3 (150 ml) outperformed the other doses, highlighting the importance of bio-stimulants in optimizing plant development by improving root architecture and plant height.

3.7 Effects of Interactions Between Different Nutrient Recipes and Bio-Stimulant Dosages on Parameters Taken at the End of Experiment

In table 6, results showed that F2D3 outperformed the other options, having the greatest numbers regarding dry root weight and stem length.

Table 6. Effect of interactions between nutrient recipes and bio-stimulant dosages on dry root weight (g) and stem length (cm)

Source of variation:	Mean ± Standard deviation	
	Dry root weight (g):	Stem length (cm):
F1D1	128.00±6.93	130.13±0.67
F1D2	192.67±4.16	139.57±0.42
F1D3	374.67±37.17	147.77±1.91
F1D0	82.00±8.72	122.87±1.72
F2D1	130.00±10.39	133.40±1.65
F2D2	208.67±18.58	142.10±2.38
F2D3	398.00±50.24	148.47±1.50
F2D0	84.67±12.06	123.20±2.55

The ANOVA results revealed that the interaction between different nutrient recipes and bio-stimulant dosages had no significant effect on dry root weight and stem length (P-value > 0.05). Despite the lack of statistical significance, there was a notable difference between the highest and lowest averages, with F2D3 generating the greatest dry root weight (398.00±50.24 g) and F1D0 producing the lowest (82.00±8.72 g). A comparative study on *Capsicum annuum* L. indicated that the combination of PGPR and NPK fertilizers had no significant effect on root dry weight, but varied PGPR concentrations did (Ichwan *et al.,* 2023). Furthermore, it is well acknowledged that the use of adequate mineral fertilizers is critical for improving soil conditions, increasing fertility, and increasing crop yield (Uzakbaevna, 2022). Regarding stem length, F2D3 surpassed F1D0, with averages of 148.47±1.50 cm and 122.87±1.72 cm, respectively. PGPR alters plant physiology, increasing nutrient absorption and root activity efficiency (Khoso *et al.,* 2023). Although the interaction did not reach statistical significance, the combination of bio-stimulants and fertilizers has been proven to improve crop output and overall plant growth (Biernacik *et al*., 2018). A previous study has shown that the benefits of bio-stimulants vary depending on the combination with various fertilizers. For example, bio-stimulants mixed with phosphorus and potassium increase yields and stimulate overall plant development (Biernacik *et al.,* 2018). Although the interaction effect was not significant, F2D3 consistently outperformed the other treatments in both dry root weight and stem length, suggesting its better efficacy in improving plant growth characteristics.

4. Conclusion

This research demonstrates that tailored nutrient solutions and appropriate bio-stimulant dosages can significantly improve the growth and yield of *Capsicum annuum* in hydroponic systems. Nutrient solution F2, with greater potassium levels, and bio-stimulant dose D3 (150 ml), were the most successful in increasing fruit count, yield, and vegetative growth. Notably, D0 (control) increased fruit size, and the interaction between nutrient recipes and bio-stimulant dosages had a significant effect on important parameters, with F2D3 generating the best total yield. Future studies should explore the long-term effects of these treatments and their economic viability in commercial production settings. Furthermore, using advanced agricultural technology such as precision fertigation systems and climate-controlled greenhouses has the potential to increase hydroponic *Capsicum annuum* crop productivity and resource efficiency.

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