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A comparative study of Bio, nano NPK with Granular NPK fertilizers on growth and yield of Sweet Pepper (Capsicum anuum).

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ABSTRACT

This study conducted at Bakrajo Technical Institute Sulaimani, Iraq, to investigates the impact of different fertilizer treatments including foliar nano NPK, bio-fertilizers, and granular NPK (1, 1.5and 2) g L-1 on the growth and yield of sweet pepper (Capsicum annuum). Utilizing Duncan's Multiple Range Test at a 95% confidence level, the statistical analysis revealed that all fertilizer treatments significantly enhanced plant height compared to the untreated plants or just keep control group, which recorded 52.3 cm. The highest plants were observed by using NPK at (95 cm) with foliar nano NPK (95.0 cm) and bio-fertilizers (93.1 cm). Notably, increasing the fertilizer concentration beyond 1 ml L^{-1} did not result in further height improvement. A similar pattern was observed for branch number and fresh yield, where 1 ml L^{-1} concentrations of bio and nano fertilizers outperformed granular NPK. Furthermore, all treatments contributed to a significant raise in dry matter accumulation, with the highest mean dry weight of 297.2 g recorded under 1 ml L^{-1} foliar nano NPK treatment. Positive correlations among plant height branch number, and leaf count further underscore the beneficial role of nano and bio-fertilizers in enhancing vegetative growth. These results highlight the importance of optimizing fertilizer type and dosage to achieve maximum productivity in sweet pepper cultivation. The study includes that precise application of nano and bio-fertilizers, particularly at 1 ml L^{-1}, offers effective alternative to traditional granular NPK, promoting both growth and yield. However, additional research is recommended to investigate the long-term impacts and to elucidate the underlying molecular mechanisms responsible for these observed growth responses and the treatments applied in this study were a control (no fertilizer), foliar nano NPK fertilizer at 1,1.5, and 2 ml L^{-1}, bio-fertilizer at 1, 1.5, and 2 ml L^{-1}, and granular NPK fertilizer at 1, 1.5, and 2 g L^{-1}.

Keywords: Sweet pepper, Nano NPK fertilizer, Biofertilizer, NPK granular fertilizer, Capsicum annuum L.

INTRODUCTION

Sweet pepper (Capsicum annuum L.), a member of the Solanaceae family, is celebrated for its vibrant colors and flavors and rich nutritional profile [1]. It is an excellent source of vitamins A and C and essential minerals such as calcium, iron, phosphorus, proteins, and carbohydrates [2,3]. To address these deficiencies, foliar spraying of fertilizers has proven effective, allowing for enhanced nutrient uptake and metabolic adjustments within plant cells [4]. Nano NPK fertilizers have shown promising effects on sweet pepper cultivation by enhancing nutrient uptake, improving growth rates, and increasing yield [5]. The nanoscale particles allow for better absorption of essential nutrients nitrogen, phosphorus, and potassium, resulting in more efficient plant utilization [6].

Moreover, the controlled-release properties of nano fertilizers reduce nutrient losses via leaching, thereby ensuring prolonged nutrient availability and improved synchronization with plant nutrient demand throughout the growth cycle. The application of nano NPK fertilizers thus holds considerable potential for enhancing the sustainability and productivity of sweet pepper (Capsicum annuum) cultivation [7]. The application of granular NPK fertilizer (20:20:20) markedly improves vegetative growth parameters and fruit yield in sweet pepper (Capsicum annuum) by supplying balanced proportions of essential macronutrients nitrogen, phosphorus, and potassium—crucial for optimal plant development [8]. This balanced fertilizer, containing equal parts nitrogen, phosphorus, and potassium, promotes robust vegetative growth, leading to lush foliage and strong stems [9]. Nitrogen supports healthy leaf development, while phosphorus stimulates root growth and flowering, producing a higher fruit set. Potassium is crucial in fruit quality, enhancing size, color, and flavor [10]. Additionally, the even distribution of nutrients helps prevent deficiencies, ensuring that the plants can effectively absorb what they need throughout their growth cycle [11]. Using NPK (20:20:20) contributes to vigorous, productive sweet pepper plants, ultimately leading to a more abundant and high-quality harvest [12,13]. By promoting beneficial microbial activity in the soil, biofertilizers improve nutrient availability and uptake, particularly nitrogen and phosphorus, which are crucial for plant development [13,14]. An in-depth comparison between nano NPK biofertilizer and traditional granular NPK fertilizer (20:20:20) in the cultivation of sweet pepper—a key crop within the Solanaceae family—has revealed substantial variations in vegetative growth, reproductive development, and overall yield. The use of nano NPK not only enhanced nutrient uptake efficiency but also contributed to improved physiological performance, suggesting its potential benefits for other Solanaceous crops such as tomato and eggplant in terms of both productivity and sustainable nutrient management [15]. The integration of nano NPK fertilizers with biofertilizers has been shown to markedly improve nutrient delivery systems and significantly elevate the bioavailability of essential macro- and micronutrients within the soil environment. This synergistic combination facilitates enhanced nutrient mobility and absorption at the rhizosphere, which is particularly beneficial for members of the Solanaceae family. As a result, plants such as tomatoes, peppers, and eggplants exhibit more vigorous root system development, improved nutrient uptake efficiency, and heightened physiological performance. These improvements contribute to stronger vegetative growth, increased resilience to environmental stressors, and overall enhancement of plant vitality, yield potential, and fruit quality in Solanaceous crops. These advanced formulations facilitate quicker absorption and more precise utilization of essential elements, which are particularly beneficial for crops within the Solanaceae family, such as sweet pepper, tomato, and eggplant, known for their high nutrient demands. In contrast, conventional NPK 20:20:20 granular fertilizers, "Although traditional NPK 20:20:20 granular fertilizers are effective in supplying primary macronutrients, research conducted in Indonesia has demonstrated that these fertilizers often exhibit slower nutrient release rates and reduced uptake efficiency. Such limitations can result in increased nutrient losses through leaching and volatilization, ultimately leading to suboptimal growth and lower yield performance in Solanaceous crops, particularly under the diverse agroecological conditions found across the country [15]. As a result, sweet pepper plants treated with nano NPK often exhibit greater vigor, higher yields, and improved resistance to stress compared to those fertilized with the granular form [16]. Using nano biofertilizers represents a promising advancement in sustainable agricultural practices, particularly for high-value crops like sweet pepper. This study aims to assess and compare the impact of different fertilization methods on the vegetative growth and yield of sweet pepper (Capsicum annuum). Specifically, it investigates the effectiveness of biofertilizers and nano NPK formulations in enhancing plant growth and productivity compared to conventional NPK (20:20:20) granular fertilizers. Given the limited research on the comparative benefits of these alternative fertilizers, this study seeks to provide valuable insights into their potential advantages in improving nutrient uptake, plant vigor, and overall yield. The findings will contribute to optimizing fertilization strategies for sustainable and efficient sweet pepper cultivation.

Materials and Methods

Location and Site of Experiment

It's done in pots experiment was conducted at the Bakrajo Technical Institute, Sulaimani city, Kurdistan region, Iraq, (with coordination Latitude: 35.5531° N and Longitude: 45.3539° E) from March to November 2024 to study the effect of levels and doses of foliar (1,1.5 and 2 ml L-1) nano NPK 20:20:20 and biofertilizer compared with granular (1,1.5 and 2 g L-1) on the growth and yield of sweet pepper and the fertilization was applying in the morning.

Design of Experiment

The field experiment was conducted under open-field conditions using a Completely Randomized Design (CRD) with three replications, as the experiment was performed in pots rather than directly in the ground, which allowed for uniform control of soil conditions and minimized environmental variability. Each pot, containing a single sweet pepper (Capsicum annuum) plant, was filled with 30 kg of homogenized soil sieved through a 4 mm to ensure consistent texture and remove large particles. The treatments included three concentrations (1, 1.5, and 2 ml L^{-1}) of foliar nano NPK (20:20:20) and biofertilizers, along with three concentrations (1, 1.5, and 2 g L^{-1}) of traditional granular NPK (20:20:20). Fertilizer applications commenced 45 days after transplanting and were applied at 15-day intervals, totaling three applications during the experimental period. The use of CRD was appropriate for this pot-based study, as it allowed for random assignment of treatments while maintaining uniform environmental conditions, enabling accurate assessment of fertilizer effects on growth and yield parameters.

Nursery Bed Preparation

The nursery plastic germinator bed was prepared on February 16, 2024; sweet pepper seeds were sown at 2-3 cm depth after thorough sterilization and cleaning. After sowing, the soil was carefully watered using an acceptable irrigation method to ensure it remained moist but not waterlogged until the seedlings emerged. Once the seedlings appeared, irrigation was applied lightly with a rose can at intervals based on the soil's needs. The pots were thoroughly prepared to make the pot and soil well prepared for seedling transplantation. Thirty pots were prepared (3 fertilizer types*3 doses for each fertilizer types* 3 replication with 3 pots Control without fertilization (0) level dose. Totally thirty pots were used according to the experimental design each pots contain single plant. The initial light irrigation occurred during transplanting, with follow-up irrigations every 4 days regularly.

Statistical Analysis

The recorded data were entered into MS Excel 2019 organized by replications and treatments. The statistical analysis was conducted using XLSTAT 2019. All tests were performed at a significance Duncan's multiple range test was applied to differentiate between means. Additionally, correlation coefficients were calculated to assess the relationships among the growth and yield parameters.

Growth and yield parameters determination

The growth and yield parameters measured in this study included plant height (cm), number of branches, and number of leaves per plant, which indicate vegetative growth. Yield-related parameters included the number of fresh fruits per plant, the weight of a single fresh fruit, total fresh yield (g) per plant, and fresh fruit diameter (cm), which reflect fruit production and size. Additionally, shoot weight (g) and dry matter content (g) were recorded to assess overall plant biomass and physiological development of sweet pepper (Capsicum annuum).

Results and Discussion

Analysis of variance effects of biofertilizer and nano NPK fertilizer on plant height (cm) of Sweet Pepper (Capsicum annuum) a comparative study with granular NPK

The effects of biofertilizer and nano NPK fertilizer on the plant height of Sweet Pepper have become a critical area of research to enhance plant growth and yield sustainably. In a recent study, the statistical analysis of plant height (cm) using different fertilizer treatments revealed significant variations in growth patterns compared to granular NPK fertilizers. The data analysis, conducted using an Analysis of Variance (ANOVA), shows that the model was highly significant ($F= 71.5$, $p <0.0001$), indicating that the type of fertilizer applied had a profound impact on plant height. The biofertilizers, which often contain nitrogen-fixing bacteria or mycorrhizal fungi, help enhance nutrient availability and promote soil health, thus leading to improved plant vigor and growth. Nano NPK fertilizers, which incorporate nanoparticles to enhance nutrient uptake efficiency, showed a considerable increase in plant height compared to conventional granular NPK fertilizers. This can be attributed to the enhanced surface area and increased solubility of nutrients in the nanoform, which improves nutrient absorption by the plant roots. Several studies have corroborated these findings, emphasizing the superior efficacy of nano fertilizers over granular forms in improving nutrient delivery and growth responses [17]. The results suggest that biofertilizers and nano NPK fertilizers could be eco-friendly and efficient alternatives to conventional fertilizers, promoting plant growth and sustainability in agriculture. However, further research is necessary to optimize application rates and understand these advanced fertilizer forms' long-term soil and environmental impacts. This comparative study contributes to the growing knowledge of sustainable agricultural practices and nutrient management strategies [17].

Table 1. Effects of biofertilizer and nano NPK fertilizer on plant height (cm) of Sweet Pepper (*Capsicum annuum*): a comparative study with granular NPK

Applications	DF	Sum of squares	Mean squares	F	Pr > F
Model	29	660066.7	22760.9	71.5	< 0.0001
Error	61	19424.4	318.5		
Corrected Total	90	679491.0			

Computed against model Y=0

The data presented in Table 2 provides a comprehensive analysis of the effect of various fertilizer applications on plant height, measured in centimeters, with a 95% confidence interval and a standard error of 5.9 cm. The analysis reveals that all fertilizer treatments, including foliar nano NPK and bio-fertilizers at various concentrations (1 ml L-1, 1.5 ml L-1, 2 ml L-1), as well as granular NPK fertilizers of 1 g L-1, 1.5 g L-1, 2 g L-1, resulted in significantly higher plant heights compared to the control group of 52.3 cm. Specifically, the application of 1 ml L-1 foliar nano NPK fertilizer produced the tallest plants at 95.0 cm, followed closely by the biofertilizer at the same concentration (93.1 cm), with both treatments showing high consistency in their effects as indicated by the overlapping confidence intervals (83.1 cm to 106.9 cm for nano NPK and 81.2 cm to 105.0 cm for biofertilizer). Interestingly, increasing the concentration of fertilizers beyond 1 ml L-1 for nano NPK at 1.5 ml L-1 or biofertilizer 2 ml L-1 did not produce a statistically significant increase in plant height compared to their lower concentration counterparts, indicating potential diminishing returns at higher application rates. This trend is supported by similar observations in granular NPK applications, where even higher doses at 1.5 g L-1 and 2 g L-1 did not surpass the efficacy of the foliar treatments. The statistical analysis, performed using Duncan's multiple range test, classified all fertilizer treatments into the same group (A), suggesting that while differences exist in absolute values, the variations are not significant enough to distinguish the treatments from each other. The control group, however, exhibited a significantly lower plant height of 52.3 cm, with a distinct separation from the fertilizer-treated groups (group B). These findings suggest that foliar and granular fertilizers, particularly at lower concentrations, profoundly impact plant growth, potentially due to the enhanced nutrient uptake efficiency facilitated by foliar application methods [18]. However, further research is necessary to understand the long-term effects of these fertilizers on plant health and soil nutrient dynamics [19,20].

Table 2. Effect of application Doses/ Duncan/ analysis of the differences between the applications with a confidence interval of 95% plant height (cm)

Applications	LS means	Lower bound (95%)	Upper bound (95%)
1 ml L^{-1} Foliar nano NPK fertilizer	95a	83.1	106.9
1 ml L^{-1} Biofertilizer	93.1a	81.2	105.0
1.5 ml L^{-1} Foliar nano NPK fertilizer	90a	78.1	101.9
1.5 ml L^{-1} Biofertilizer	89.6a	77.7	101.4
1 g $^{L-1}$ Granular NPK	86a	74.1	97.9
2 ml L^{-1} Biofertilizer	86 a	74.1	97.9
2 ml L^{-1} Foliar nano NPK fertilizer	84a	72.1	95.9
1.5 gL^{-1} Granular NPK	83.2a	71.3	95.1
2 g L^{-1} Granular NPK	81.4a	69.6	93.3
Control	52.3b	42.6	62.0

Analysis of variance effects of biofertilizer and nano NPK fertilizer on branch number of sweet pepper (Capsicum annuum) a comparative study with granular NPK

In recent studies, applying biofertilizers and nano-based fertilizers has emerged as promising to enhance plant growth, particularly in crops like Sweet Pepper (Capsicum annuum). A comparative study of the effects of biofertilizers and nano NPK fertilizers on the branch number of Sweet Pepper reveals significant insights into plant nutrient management. Table 3 presents a statistical analysis of these treatments, focusing on the number of branches produced by the plant as a key growth parameter. The model's F-value of 110.6 with a p-value <0.0001 indicates a highly significant effect of the fertilizer treatments on branch number, suggesting that the fertilizer applied influences plant morphology. Biofertilizers, which often contain beneficial microorganisms, improve soil fertility and stimulate plant growth through nutrient fixation, disease suppression, and phytohormone production [21]. On the other hand, nano NPK fertilizers, with their increased surface area and enhanced nutrient release profile, offer a more efficient nutrient uptake system due to their ability to penetrate plant tissues at the nanoscale, potentially leading to improved growth rates and higher branching [22]. Granular NPK fertilizers, commonly used in conventional agriculture, provide a slower release of nutrients, which might not be as immediately effective in promoting rapid vegetative growth as their nano counterparts [23,24]. The statistical analysis supports these findings by showing that the differences between treatments are statistically significant, reinforcing nano-fertilizers' potential to outperform traditional fertilizers in promoting desirable plant traits like branch number. Future studies should further explore the molecular mechanisms behind these observed effects, focusing on nutrient uptake pathways and plant hormonal regulation in response to nano-enhanced fertilizers. This would provide deeper insights into optimizing fertilizer formulations for sustainable agricultural practices.

Table 3. Effects of biofertilizer and nano NPK fertilizer on branch number of Sweet Pepper (*Capsicum annuum*) a comparative study with granular NPK

Applications	DF	Sum of squares	Mean squares	F	Pr > F
Model	29	32979.7	1137.2	110.6	< 0.0001
Error	61	627.3	10.3		
Corrected Total	90	33607.0			
Computed against model Y=0					

The results presented in Table 4 provide insight into the effect of various fertilizer application doses on the number of branches in a plant, evaluated through Duncan's Multiple Range Test with a 95% confidence interval. The data show a clear trend in the response of branch number to increasing fertilizer doses, with bio-based and nano NPK fertilizers outperforming granular NPK formulations and the control group. Specifically, the application of 1 ml L^{-1} bio-fertilizer and 1 ml L^{-1} foliar nano NPK fertilizer resulted in the highest branch numbers of 23.8 and 23.6, respectively, which were significantly higher than all other treatments ($p<0.05$), placing them in Group A. In contrast, treatments involving higher doses of bio or nano fertilizers, such as 1.5 ml L^{-1} bio-fertilizer and 1.5 ml L^{-1} foliar nano NPK fertilizer, showed a decrease in branch number (21.4 and 22.0, respectively), though still significantly higher than granular NPK formulations and the control. This suggests that while foliar application of nano fertilizers and bio-fertilizers effectively promotes branch development, there may be an optimal dose, with excessive application leading to decreased efficiency. For granular NPK treatments, a trend of decreasing branch number with increasing application dose is evident, with 2 g L^{-1} granular NPK resulting in the lowest branch count (14.8). These findings align with previous studies that have demonstrated the superior efficacy of nano fertilizers in improving plant growth metrics due to their enhanced nutrient uptake and bioavailability [24, 25,26]. The control group, receiving no fertilizer, exhibited the lowest branch number (8.6), underscoring the importance of fertilization in promoting vegetative growth. The significant differences observed among the treatments can be attributed to variations in nutrient release rates, absorption mechanisms, and each fertilizer type's specific modes of action, with nano fertilizers offering more rapid and efficient nutrient uptake than traditional granular forms [26]. Therefore, while nano fertilizers, particularly in lower doses, show promising potential for enhancing plant growth, care must be taken to avoid excessive application, which may lead to diminishing returns.

Table 4. Effect of application doses/ Duncan/ analysis of the differences between the applications with a confidence interval of 95% branch number

Applications	LS means	Lower bound (95%)	Upper bound (95%)
1 ml L^{-1} Biofertilizer	23.8a	21.6	25.9
1 ml L^{-1} Foliar nano NPK fertilizer	23.6a	21.4	25.7
1.5 ml L^{-1} Foliar nano NPK fertilizer	22ab	19.9	24.1
1.5 ml L^{-1} Biofertilizer	21.4ab	19.3	23.6
2 ml L^{-1} Foliar nano NPK fertilizer	19.7bc	17.5	21.8
2 ml L^{-1} Biofertilizer	17.8cd	15.6	19.9
1 g L^{-1} Granular NPK	17.3cd	15.2	19.5
1.5 gL^{-1} Granular NPK	16.1d	14.0	18.2
2 g L^{-1} Granular NPK	14.8d	12.6	16.9
Control	8.6e	6.8	10.3

Analysis of variance effects of biofertilizer and nano NPK fertilizer on number of leaves plant-1 of sweet pepper (Capsicum annuum) a comparative study with granular NPK.

The impact of biofertilizers and nano NPK fertilizers on the number of leaves per plant in Capsicum annuum (sweet pepper) has become a subject of considerable interest in modern agricultural research, particularly in comparison to conventional granular NPK fertilizers. Recent studies, including those in 2024, demonstrate that using nano-fertilizers can significantly enhance nutrient uptake and plant growth, as evidenced by the data from the comparative study outlined in Table 5. The results show a highly significant F-value of 76.1 ($p < 0.0001$), indicating that applying biofertilizers and nano NPK fertilizers notably improves the number of leaves per plant compared to traditional granular NPK treatments. Nano NPK fertilizers, due to their reduced particle size, offer higher surface area and better solubility, which facilitates more efficient absorption of nutrients, particularly nitrogen, phosphorus, and potassium, essential for leaf development [27]. In contrast, biofertilizers, which include beneficial microorganisms, work synergistically with the soil microbiome, promoting nutrient cycling, enhancing soil structure, and improving plant growth by biologically fixing nitrogen and solubilizing phosphates [28]. The data from the study supports these findings, as the nano NPK treatments show superior performance in leaf number compared to granular NPK, likely due to the enhanced nutrient availability and absorption efficiency of nanoparticles. While effective, the granular NPK fertilizer has limitations in nutrient release, which may result in slower plant uptake. Therefore, the combined use of biofertilizers and nano NPK fertilizers represents a promising strategy for sustainably optimizing crop productivity, as it not only boosts plant growth but also reduces the dependency on traditional chemical fertilizers. Such integrated nutrient management systems are critical for achieving higher yields and more environmentally friendly agricultural practices.

Table 5. Effects of biofertilizer and nano NPK fertilizer on number of leaves $plant^{-1}$ of sweet pepper (*Capsicum annuum*) a comparative study with granular NPK.

Applications	DF	Sum of squares	Mean squares	F	Pr > F
Model	29	1365306.3	47079.5	76.1	< 0.0001
Error	61	37742.7	618.7		
Corrected Total	90	1403049.0			

Computed against model Y=0

The analysis of variance and Duncan's multiple range test for the effect of various fertilizer application doses on the number of leaves per plant at a 95% confidence interval reveals notable differences across treatments, with significant implications for plant growth and nutrient management strategies. Table 6 indicates that foliar nano NPK and bio-fertilizers at concentrations of 1 ml L-1 exhibited the highest leaf counts, with 140.0 and 139.3 leaves per plant, respectively, showing statistically similar results (group A), which suggests a substantial benefit of foliar applications in enhancing photosynthetic capacity and overall plant vigor. However, as the concentration of fertilizers increased, a slight reduction in leaf count was observed, particularly at 1.5 ml L-1 for both foliar nano NPK and biofertilizers (133.6 and 131.4 leaves, respectively), yet these treatments still grouped with the initial higher doses (group A and B). This trend is consistent with findings from recent research, which suggests that while nutrient concentration is essential for plant development, excessive doses may result in nutrient imbalance or toxicity that can hinder optimal leaf production [29]. In contrast, granular NPK applications at doses of 1 g L-1 and 1.5 g L-1 displayed a downward trend in leaf number of 120.2 and 113.7, respectively, aligning with the notion that granular fertilizers, though adequate for long-term nutrient release, may not be as immediately bioavailable to plants as foliar treatments, limiting their efficacy in the short term. The lowest number of leaves per plant was recorded in the control treatment, with 71.3 leaves, highlighting the importance of fertilization in promoting leaf development. This pattern of results suggests that the appropriate choice of fertilizer type and application rate is critical for optimizing leaf production, with foliar nano fertilizers being the most effective option in this study. Further research is warranted to explore the physiological mechanisms underlying these differences and to refine application protocols for improved crop management [30].

Table 6. Effect of application doses/ Duncan/ analysis of the differences between the applications with a confidence interval of 95% number of leaves plant^{-1}.

Applications	LS means	Lower bound (95%)	Upper bound (95%)
1 ml L-1 Foliar nano NPK fertilizer	140a	123.4	156.6
1 ml L-1 Biofertilizer	139.3a	122.8	155.9
1.5 ml L-1 Foliar nano NPK fertilizer	133.6ab	117.0	150.1
1.5 ml L-1 Biofertilizer	131.4ab	114.9	148.0
2 ml L-1 Biofertilizer	123.2ab	106.6	139.8
2 ml L-1 Foliar Nano NPK fertilizer	122.3ab	105.8	138.9
1 g L-1 Granular NPK	120.2ab	103.6	136.8
1.5 gL-1 Granular NPK	113.7ab	97.1	130.2
2 g L-1 Granular NPK	111b	94.4	127.6
Control	71.3c	57.8	84.9

Analysis of variance effects of biofertilizer and nano NPK fertilizer on number of fresh fruits per plant-1 of sweet pepper (Capsicum annuum) a comparative study with granular NPK.

The data presented in Table 7 demonstrate the significant effects of biofertilizer and nano NPK fertilizer on the number of fresh fruits per plant of sweet pepper (Capsicum annuum), as compared to granular NPK fertilizer, with a highly significant statistical result ($p<0.0001$). The model sum of squares (3895.7) and mean squares (134.3) indicate a strong relationship between fertilizer treatments and fruit yield, as evidenced by the computed F-value of 107.3. These results align with recent findings in agricultural biotechnology, where nano fertilizers, particularly nano NPK, have shown promising improvements in plant nutrient uptake efficiency, leading to enhanced growth and fruit production. Nano NPK fertilizers provide a controlled release of nutrients, which optimizes the bioavailability of nitrogen, phosphorus, and potassium, which are crucial for fruit development [31]. Similarly, biofertilizers, containing beneficial microorganisms, improve soil health and nutrient cycling, promoting plant vigor and increasing fruit set. The comparative superiority of nano NPK over conventional granular fertilizers can be attributed to nanomaterials' higher surface area and reactivity, facilitating faster absorption and more efficient nutrient transport within the plant. This study underscores the potential of integrating nano-fertilization and bio-inoculants in sustainable agricultural practices, enhancing crop productivity with reduced environmental impact. The F-value and low p-value also suggest a robust model, emphasizing the efficacy of these treatments in boosting fruit yield, which is crucial for optimizing agricultural productivity and supporting food security [32,33]. Future research should further explore the synergistic effects of combining these technologies, examining their long-term sustainability and effects on plant health and soil ecology.

Table 7. Effects of biofertilizer and nano NPK fertilizer on number of fresh fruits per plant^{-1} of sweet pepper (*Capsicum annuum*) a comparative study with granular NPK.

Applications	DF	Sum of squares	Mean squares	F	Pr > F
Model	29	3895.7	134.3	107.3	< 0.0001
Error	61	76.3	1.3		
Corrected Total	90	3972.0			
		Computed against model Y=0			

The analysis presented in Table 8 reveals significant differences in the number of fresh fruits per plant as influenced by varying application doses of biofertilizers, foliar nano NPK fertilizers, and granular NPK fertilizers, with a 95% confidence interval. The statistical groupings (A, B, C, D) show clear trends in efficacy among the treatments. The freshest fruits per plant were recorded with the 1 ml L-1 biofertilizer application (9.22 fruits), significantly higher than all other treatments. This result aligns with studies suggesting that bio-based fertilizers enhance plant growth and fruit production by improving nutrient availability, stimulating microbial activity in the rhizosphere, and enhancing plant stress tolerance [34]. Conversely, the 1.5 ml L-1 foliar nano NPK fertilizer and higher doses of granular NPK fertilizers 1.5 g L-1 and 2 g L-1 exhibited comparatively lower fruit yields, ranging from 5.11 to 7.67 fruits per plant. This may be attributed to the imbalance or slow-release nature of granular NPK fertilizers, which can lead to nutrient stress or toxicity at higher concentrations [22]. Additionally, the control group, which received no fertilizer application, showed the lowest fruit yield (3.11 fruits per plant), highlighting the importance of nutrient supplementation for optimal plant productivity. The statistical analysis, conducted using Duncan's multiple range test, further underscores the significant superiority of bio-fertilizer applications over all other treatments, particularly in fruit production. These findings suggest that due to their holistic effects on soil health and nutrient cycling, bio-fertilizers offer a sustainable and efficient alternative to synthetic fertilizers for enhancing crop yield, particularly in environments where minimizing chemical inputs is a priority [35]. The application of foliar nano NPK fertilizers also showed promise, although their effect was less pronounced than bio-fertilizers, likely due to their rapid uptake mechanism, which may not have been fully optimized for fruiting in the conditions tested. Future research could focus on optimizing these formulations for enhanced crop yield.

Table 8. Effect of application doses/ Duncan/ analysis of the differences between the applications with a confidence interval of 95% number of fresh fruits per plant^{-1}.

Applications	LS means	Lower bound (95%)	Upper bound (95%)
1 ml L^{-1} Biofertilizer	9.22a	8.48	9.97
1.5 ml L^{-1} Biofertilizer	7.67b	6.92	8.41
1 ml L^{-1} Foliar nano NPK fertilizer	7.33b	6.59	8.08
2 ml L^{-1} Biofertilizer	7.11b	6.37	7.86
1.5 ml L^{-1} Foliar Nano NPK fertilizer	6c	5.25	6.75
1.5 gL^{-1} Granular NPK	5.89c	5.14	6.63
1 g L^{-1} Granular NPK	5.22c	4.48	5.97
2 ml L^{-1} Foliar Nano NPK fertilizer	5.22c	4.48	5.97
2 g L^{-1} Granular NPK	5.11c	4.37	5.86
Control	3.11d	2.50	3.72

Analysis of variance effects of biofertilizer and nano NPK fertilizer on weight of one fresh fruit per plant-1 of sweet pepper (Capsicum annuum) a comparative study with granular NPK.

The application of biofertilizers and nano-formulated fertilizers in agricultural practices has garnered significant attention in recent years due to their potential to enhance crop yields while minimizing environmental impacts. In a comparative study examining the effects of biofertilizers and nano NPK fertilizers on the weight of one fresh fruit per plant in sweet pepper (Capsicum annuum), a statistical analysis (Table 9) revealed highly significant differences between treatment groups, as indicated by an F-value of 233.4 with a p-value <0.0001. This suggests that biofertilizers and nano NPK fertilizers significantly influence fruit development compared to traditional granular NPK applications. Biofertilizers, which often contain beneficial microorganisms, can improve nutrient uptake and enhance soil health, leading to better plant growth and increased fruit yield [36]. On the other hand, nano NPK fertilizers offer advantages through their high surface area and controlled release properties, which ensure a more efficient nutrient supply to plants, potentially improving plant metabolism and fruiting capacity [37]. The greater effectiveness of nano fertilizers in delivering nutrients at the microscale and their ability to target specific plant needs likely contributed to the superior fruit weight observed in this study. Moreover, the substantial statistical significance of these treatments (F=233.4) underscores their potential as sustainable alternatives to conventional fertilizers. These findings align with recent research that suggests nano fertilizers may improve nutrient use efficiency and environmental sustainability, offering a promising solution for modern agricultural practices [38].

Table 9. Effects of biofertilizer and nano NPK fertilizer on the weight of one fresh fruit per plant^{-1} (g) of sweet pepper (*Capsicum annuum*) a comparative study with granular NPK.

Applications	DF	Sum of squares	Mean squares	F	Pr > F
Model	29	19673.7	678.4	233.4	< 0.0001
Error	61	177.3	2.9		

Corrected Total	90	19851.0

Computed against model Y=0

The results presented in Table 10 regarding the effect of different application doses on the weight of fresh fruit per plant provide valuable insights into the efficacy of various fertilizers on plant growth and yield. The data highlights significant differences in fruit weight between different fertilizer treatments, as analyzed using Duncan's Multiple Range Test (DMRT) at a 95% confidence interval. For instance, both the 1 ml L-1 Biofertilizer and the 1 ml L-1 Foliar nano NPK fertilizer yielded the highest average fresh fruit weight per plant (20.3 g and 20.0 g, respectively), with no significant difference between them, as indicated by their classification into the same group (A). This suggests that bio and nano NPK foliar fertilizers are highly effective in promoting fruit weight, likely due to their bioavailability and nutrient release kinetics [39]. In contrast, the higher concentrations of both bio and nano NPK fertilizers (1.5 ml L-1 and 2 ml L-1) resulted in reduced fruit weight (14.9 g to 18.3 g), suggesting a possible nutrient overload or imbalanced application, which may hinder optimal nutrient uptake or lead to nutrient toxicity [37,40]. Similarly, the granular NPK treatments at 1 g L-1, 1.5 g L-1, and 2 g L-1 resulted in progressively lower fruit weights (13.0 g to 9.6 g), likely due to slower nutrient release and less efficient absorption compared to the more soluble liquid fertilizers [17]. The control group, which received no fertilizer application, recorded the lowest fruit weight (4.9 g), further validating the importance of fertilization for enhancing crop yield. The confidence intervals for each treatment further support the significance of these differences, with all treatments showing distinct statistical groupings (A, B, C, D, E, F). These findings underscore the importance of fertilizer type, dosage, and application method in influencing plant growth and productivity, aligning with recent research on optimizing nutrient delivery for sustainable agricultural practices.

Table 10. Effect of application doses/ Duncan/ analysis of the differences between the applications with a confidence interval of 95% weight of one fresh fruit per plant^{-1} (g).

Applications	LS means	Lower bound (95%)	Upper bound (95%)
1 ml L^{-1} Biofertilizer	20.3a	19.2	21.5
1 ml L^{-1} Foliar nano NPK fertilizer	20a	18.9	21.1
1.5 ml L^{-1} Foliar nano NPK fertilizer	18.3b	17.2	19.5
2 ml L^{-1} Biofertilizer	14.9c	13.8	16.0
1.5 ml L^{-1} Biofertilizer	14.8c	13.6	15.9
2 ml L^{-1} Foliar nano NPK fertilizer	14cd	12.9	15.1
1 g L^{-1} Granular NPK	13d	11.9	14.1
1.5 gL^{-1} Granular NPK	10.1e	9.0	11.2
2 g L-1 Granular NPK	9.6e	8.4	10.7
Control	4.9f	4.0	5.8

Analysis of variance effects of biofertilizer and nano NPK fertilizer on weight of fresh yield (g) per plant-1 of sweet pepper (Capsicum annuum) a comparative study with granular NPK.

In the study presented in Table 11, the effects of biofertilizer and nano NPK fertilizer on the fresh yield weight (g) per plant of sweet pepper (Capsicum annuum) were evaluated, with a focus on comparing the performance of these treatments against granular NPK fertilizer. The analysis reveals a significant difference between the treatments, as indicated by a highly significant F-value (349.4) and a p-value less than 0.0001. This means that the differences observed in the fresh yield weight are unlikely to have occurred due to climate. The model accounts for 29 degrees of freedom (DF) and has a sum of squares of 1,589,055.3, with a mean square of 54,795.0. These results suggest that the fertilizers applied (biofertilizer and nano NPK) significantly influence the yield of sweet pepper plants. Significant effects are of interest because they provide evidence that the treatment applied (biofertilizer or nano NPK) has a statistically meaningful impact on plant growth, which can guide agricultural practices and decision-making.

On the other hand, non-significant results would indicate no clear evidence that one fertilizer is superior over another for improving yield. The significant finding here aligns with current research indicating the benefits of nano fertilizers in improving nutrient delivery efficiency and plant growth [41]. These findings are relevant as they inform the scientific community and agricultural practitioners about effective fertilization strategies for optimizing crop yields.

Table 11. Effects of biofertilizer and nano NPK fertilizer on the weight of fresh yield (g) per plant^{-1} of sweet pepper (*Capsicum annuum*) a comparative study with granular NPK.

Applications	DF	Sum of squares	Mean squares	F	Pr > F
Model	29	1589055.3	54795.0	349.4	< 0.0001
Error	61	9566.7	156.8		
Corrected Total	90	1598622.0			
Computed against model Y=0					

This study analyzed the effect of various application doses of biofertilizers and nano NPK fertilizers on the fresh yield weight (g) per plant using a 95% confidence interval and Duncan's Multiple Range Test. The results presented in Table 12 indicate that the different fertilizer applications significantly influenced plant weight, with distinct groups identified based on statistical significance. The 1 ml L-1 biofertilizer treatment (170.4 g) was the most effective, grouped as "A," showing the highest yield, followed by 1 ml L-1 foliar nano NPK fertilizer (169.7 g), also grouped as "A." The yield progressively decreased with higher doses of both fertilizers, especially at 2 ml L-1 biofertilizer (149.6 g) and 2 ml L-1 foliar nano NPK fertilizer (129.7 g), indicating reduced efficacy with increasing fertilizer concentration. These findings suggest that lower doses of bio and nano NPK fertilizers might optimize plant growth and yield, while higher doses lead to diminishing returns. The statistical analysis using Duncan's test highlighted significant differences between the application groups, with lower doses consistently yielding better results. The findings are supported by the standard errors and 95% confidence intervals confirming the differences' robustness (the lower bound of 1 ml L-1 biofertilizer is 162.1 g, and the upper bound is 178.8 g) [42]. The significance of these results lies in the potential for optimizing fertilizer use, ensuring both economic and environmental benefits by applying the appropriate dose for maximum yield. However, higher fertilizer doses could be non-significant in terms of additional yield improvement, thus suggesting inefficiency beyond certain application thresholds.

Table 12. Effect of application doses/ Duncan/ analysis of the differences between the applications with a confidence interval of 95% weight of fresh yield (g) per plant^{-1}.

Applications	LS means	Lower bound (95%)	Upper bound (95%)
1 ml L^{-1} Biofertilizer	170.4a	162.1	178.8
1 ml L-1 Foliar nano NPK fertilizer	169.7ab	161.3	178.0
1.5 ml L^{-1} Foliar nano NPK fertilizer	159.8abc	151.4	168.1
1.5 ml L^{-1} Biofertilizer	157.3bc	149.0	165.7
2 ml L^{-1} Biofertilizer	149.6c	141.2	157.9
2 ml L^{-1} Foliar Nano NPK fertilizer	129.7d	121.3	138.0
1 g L^{-1} Granular NPK	95.9e	87.5	104.2
1.5 gL^{-1} Granular NPK	87.9e	79.5	96.2
2 g L^{-1} Granular NPK	72.7f	64.3	81.0
Control	48.4g	41.6	55.3

Analysis of variance effects of biofertilizer and nano NPK fertilizer on fresh fruit diameter (cm) of sweet pepper (Capsicum annuum) a comparative study with granular NPK.

In the study conducted on the effects of biofertilizer and nano NPK fertilizer on the fresh fruit diameter (cm) of sweet pepper (Capsicum annuum), as outlined in Table 13, the analysis of variance (ANOVA) results reveals highly significant findings. The model with a degree of freedom (DF) of 29 showed a sum of squares of 2818.51 and a mean square of 97.19, resulting in an F-value of 104.10. The corresponding p-value (Pr> F) of <0.0001 indicates that the differences observed in the fresh fruit diameter are statistically significant at a 95% confidence level. This suggests that applying biofertilizer and nano NPK fertilizers significantly influences the growth of sweet pepper fruits, outperforming conventional granular NPK fertilizers in terms of fruit diameter. The model's high F-value and low p-value demonstrate that the experimental treatments led to a considerable difference in fruit diameter, rejecting the null hypothesis (Y= 0). Such significant findings imply that biofertilizers and nano NPK fertilizers may enhance nutrient uptake and plant growth, providing a potentially sustainable alternative to conventional fertilizers [17,41]. This supports the growing interest in integrating nano-technology and bio-based products in agricultural practices to optimize crop yields while reducing environmental impact. The significant result is denoted by a p-value of <0.0001, indicating that the observed effect is highly unlikely to have occurred by chance. The contrast with a non-significant p-value (typically greater than 0.05) would suggest that no meaningful difference exists between treatments, which in this case is not observed, emphasizing the effectiveness of the fertilizers tested.

Table 13. Effects of biofertilizer and nano NPK fertilizer on fresh fruit diameter (cm) of sweet pepper (*Capsicum annuum*): a comparative study with granular NPK.

Applications	DF	Sum of squares	Mean squares	F	Pr > F
Model	29	2818.51	97.19	104.10	< 0.0001
Error	61	56.95	0.93		
Corrected Total	90	2875.46			

Computed against model Y=0

In the study presented in Table 14, the effect of different fertilizer applications on the fresh fruit diameter (cm) was analyzed using Duncan's multiple range test at a 95% confidence interval. The results indicate significant differences in fruit diameter across the various treatments, with the application of 1 ml L-1 Foliar nano NPK fertilizer (7.9 cm) leading to the highest fruit diameter, followed by 1 ml L-1 Biofertilizer (7.0 cm). The lowest fruit diameter was observed in the control group (2.8 cm), which had significantly smaller fruit than all fertilizer treatments. Statistically, the treatments fell into distinct groups based on their means, with overlapping confidence intervals indicating non-significant differences within groups. For instance, the treatments of 1 ml L-1 Foliar nano NPK fertilizer and 1 ml L-1 Biofertilizer both formed group A, while higher application doses of nano NPK fertilizer and Biofertilizer resulted in smaller fruit diameters, categorizing them into lower groups such as C, D, and E. These results suggest that lower concentrations of nano NPK fertilizer (1 ml L-1) are more effective in promoting fruit growth, likely due to the higher availability of nutrients to the plant in a readily absorbable form. In contrast, higher doses may lead to nutrient imbalances or toxicity, reducing fruit size. Granular NPK applications showed consistently lower fruit diameters, indicating that the foliar route may offer superior nutrient uptake efficiency. This finding underscores the significance of optimizing fertilizer concentration for enhanced agricultural productivity [43].

Table 14. Effect of application doses/ Duncan / analysis of the differences between the applications with a confidence interval of 95% fresh fruit diameter in (cm).

Applications	LS means	Lower bound (95%)	Upper bound (95%)
1 ml L^{-1} Foliar nano NPK fertilizer	7.9ab	7.3	8.6
1 ml L^{-1} Biofertilizer	7ab	6.4	7.7
1.5 ml L^{-1} Foliar nano NPK fertilizer	6.1bc	5.5	6.8
1.5 ml L^{-1} Biofertilizer	5.6cd	5.0	6.3
2 ml L^{-1} Foliar nano NPK fertilizer	5.3cd	4.7	6.0
2 ml L^{-1} Biofertilizer	4.9de	4.3	5.6
2 g L^{-1} Granular NPK	4.9de	4.2	5.5
1 g L^{-1} Granular NPK	4.9de	4.2	5.5
1.5 gL^{-1} Granular NPK	4.3e	3.6	4.9
Control	2.8f	2.3	3.4

Analysis of variance effects of biofertilizer and nano NPK fertilizer on shoots weight in (g) of sweet pepper (Capsicum annuum) a comparative study with granular NPK.

In the study examining the effects of biofertilizer and nano NPK fertilizer on the shoot weight of sweet pepper (Capsicum annuum), a statistical analysis was conducted to determine the significance of the treatments compared to granular NPK fertilizer. The analysis of variance (ANOVA) results presented in Table 15 reveal a highly significant effect of the treatment model ($p < 0.0001$), with an F-value of 92.1. This suggests that the variation in shoot weight among the different fertilizer treatments is not due to random chance but rather the influence of the biofertilizer and nano NPK fertilizer applications. The significant p-value (< 0.0001) indicates that the observed effects on shoot weight are statistically meaningful. This finding supports the idea that the type of fertilizer (biofertilizer, nano NPK, or granular NPK) is crucial in optimizing plant growth and shoot development in sweet pepper cultivation. In contrast, the error sum of squares and mean squares indicates that the random variation (error) is relatively small compared to the treatment effects, reinforcing the robustness of the results. In this case, the significance of the treatment effects is crucial for further agricultural practices, as it may suggest that nano NPK or biofertilizer could provide more efficient or environmentally friendly alternatives to traditional granular NPK fertilizers to enhance crop yield and promote plant growth. The p-value of < 0.0001 indicates a highly statistically significant result, meaning there is a less than 0.01% chance that the observed differences in shoot weight occurred due to random variation. This strong significance level provides confidence that the fertilizers effectively influenced shoot weight. While this study shows significant overall effects, non-significant results within specific subgroups or fertilizer treatments would be expected if the variation among these treatments were slight or if there were confounding variables not controlled for in the analysis [44]. Further breakdown and post-hoc tests might be necessary to pinpoint where non-significant results may occur, which can help refine the choice of fertilizer for targeted growth conditions.

Table 15. Effects of biofertilizer and nano NPK fertilizer on shoots weight (g) of sweet pepper (*Capsicum annuum*): a comparative study with granular NPK.

Applications	DF	Sum of squares	Mean squares	F	Pr > F
Model	29	15604152.0	538074.2	92.1	< 0.0001
Error	61	356468.0	5843.7		
Corrected Total	90	15960620.0			
		Computed against model Y=0			

In Table 16, the analysis of the effect of various fertilizer applications on shoot weight (g) is presented using a confidence interval of 95%. The results show that all fertilizer treatments, including foliar nano NPK and bio-fertilizers at different concentrations and granular NPK at various doses, resulted in shoot weights significantly higher than the control treatment, which had the lowest shoot weight (256.6 g). The least significant difference (LS means) values for all fertilizer treatments ranged between 398.9 g and 452.6 g, with standard errors of 25.5 g across treatments. Despite these variations, all fertilizer applications (foliar and granular) exhibited similar shoot weights, as indicated by their overlapping confidence intervals (lower bound: 347.9 g to 503.5 g). The control group (256.6 g), with confidence intervals ranging from 215.0 g to 298.2 g, is distinct, showing significantly lower results than any fertilizer treatment. Therefore, although there is no significant difference in shoot weight between the different fertilizer treatments (all grouped as 'A'), the significant difference between fertilizer applications and the control treatment underscores the effectiveness of the fertilizers in promoting shoot growth. These findings suggest that applying foliar or granular fertilizers is crucial for enhancing shoot weight compared to no fertilizer application. This context refers to the lack of meaningful differences between the fertilizer application types but clear differentiation between fertilized and control groups. This statistical outcome is supported by Duncan's test for multiple comparisons, which showed no significant difference between the fertilizer treatments but a clear contrast with the control. The lack of significant difference within fertilizer treatments suggests that the varying concentrations of fertilizers did not drastically influence the shoot weight, indicating a plateau in effectiveness once the fertilizers were applied [45].

Table 16. Effect of application doses/ Duncan/ analysis of the differences between the applications with a confidence interval of 95% shoot weight in (g).

Applications	LS means	Lower bound (95%)	Upper bound (95%)
1 ml L^{-1} Foliar nano NPK fertilizer	452.6a	401.6	503.5
1 ml L^{-1} Biofertilizer	444.3a	393.4	495.3
1.5 ml L^{-1} Foliar nano NPK fertilizer	441.3a	390.4	492.3
1.5 ml L^{-1} Biofertilizer	432.2a	381.3	483.2
2 ml L^{-1} Foliar nano NPK fertilizer	430.4a	379.5	481.4
1 g L^{-1} Granular NPK	418.7a	367.7	469.6
1.5 gL^{-1} Granular NPK	410.4a	359.5	461.4
2 g L^{-1} Granular NPK	403a	352.0	454.0
2 ml L^{-1} Biofertilizer	398.9a	347.9	449.8
Control	256.6b	215.0	298.2

Analysis of variance effects of biofertilizer and nano NPK fertilizer on dry matter in (g) of sweet pepper (Capsicum annuum) a comparative study with granular NPK.

In the experiment presented in Table 17, the effect of biofertilizer and nano NPK fertilizer on dry matter (g) of sweet pepper (Capsicum annuum) was analyzed using statistical methods to test the significance of treatments. Results show that the F-value for the model was 91.1 and the p-value was less than 0.0001, the effect of biofertilizer and nano NPK fertilizer on dry matter production is statistically significant. This shows that the treatments greatly influence sweet pepper development and that differences observed in dry matter are unlikely to be due to chance. The analysis shows that biofertilizers and nano NPK fertilizers effectively influence plant biomass, potentially increasing nutrient uptake and overall plant health compared to regular granular NPK application. This is because of the enhanced bioavailability of nutrients in nano fertilizers and biofertilizer growth-promoting potential, which can lead to enhanced dry matter accumulation in plants [17,45]. Moreover, the correlation between shoot weight (g/plant) and dry matter content indicates that shoot weight and dry matter accumulation increase together. This correlation shows that treatments that enhance shoot biomass are to blame for the rise in dry matter content, further enhancing the importance of biofertilizers and nano NPK fertilizers in promoting total plant productivity.

Understanding this correlation is important to optimize fertilization strategies in sustainable agriculture. However, when interpreting such statistical results, it should be taken into account that while the model shows important effects, further examination of the unique contributions of each fertilizer type would determine which treatment(s) perform best under varying environmental conditions. This can be achieved through further experimentation and more advanced statistical analysis, such as examining interaction effects between fertilizer type and environmental variables (45).

Table 17. Effects of biofertilizer and nano NPK fertilizer on sweet pepper dry matter (g) (*Capsicum annuum*): a comparative study with granular NPK.

Applications	DF	Sum of squares	Mean squares	F	Pr > F
Model	29	6727628.4	231987.2	91.1	< 0.0001
Error	61	155271.3	2545.4		
Corrected Total	90	6882899.8			
		Computed against model Y=0			

The values in Table 18 indicate the shoot weight (g) per plant against dry matter (g) under different fertilizer treatments. The increase in dry matter was observed in all treatments compared to the control, which had the lowest mean dry matter value (168.1 g). The same is true with shoot weight per plant because more shoot biomass is likely to be linked with more dry matter accumulation. The highest dry matter content (297.2 g) was achieved with 1 ml L^{-1} foliar nano NPK fertilizer, showing the role played by nutrient supplementation to elongation of shoots and dry matter. Duncan's test grouped all fertilizer treatments into the same statistical category (A), indicating that diversified formulations, nano, bio, or granular, made an equivalent contribution to plant biomass. The dry matter value of the control group was much lower and was separated into a group (B), reaffirming the requirement of fertilization for improving plant growth. The findings validate the direct relationship between shoot weight and dry matter accumulation, indicating that greater nutrient uptake through fertilization leads to more biomass production, a factor imperative to maximize crop yield.

Table 18. Effect of application doses/Duncan/ analysis of the differences between the applications with a confidence interval of 95% dry matter (g)

Applications	LS means	Lower bound (95%)	Upper bound (95%)
1 ml L^{-1} Foliar nano NPK fertilizer	297.2a	263.5	330.8
1 ml L^{-1} Biofertilizer	291.8a	258.1	325.4
1.5 ml L^{-1} Foliar Nano NPK fertilizer	289.8a	256.2	323.4
1.5 ml L^{-1} Biofertilizer	283.8a	250.2	317.4
2 ml L^{-1} Foliar nano NPK fertilizer	282.7a	249.1	316.3
1 g L^{-1} Granular NPK	274.9a	241.3	308.6
1.5 gL^{-1} Granular NPK	269.5a	235.9	303.2
2 g L^{-1} Granular NPK	264.6a	231.0	298.3
2 ml L^{-1} Biofertilizer	261.9a	228.3	295.6
Control	168.1b	140.6	195.5

The correlation coefficient of biofertilizer and nano NPK fertilizer on growth and yield of sweet pepper (Capsicum annuum) a comparative study with granular NPK.

In the data in Table 19, the correlation coefficients represent the relationship between various growth and yield parameters of sweet pepper (Capsicum annuum) under biofertilizer and nano NPK fertilizer treatments, compared to granular NPK. A detailed examination of these correlations reveals strong and weak associations among the parameters. For instance, plant height (cm) shows a highly significant correlation (r = 0.93 to 1.00) with branch number, number of leaves, and weight of one seed per plant, suggesting a robust positive relationship where increases in plant height are associated with greater branching and leaf development. Conversely, parameters like the number of fresh fruits per plant (r = 0.36 to 0.49) exhibit weak correlations with other growth characteristics, implying that while fruit number positively correlates with yield traits, other growth parameters do not strongly influence it. The significance of these correlations is evaluated at a p-value of 0.05, where values greater than 0.5 (e.g., plant height with number of leaves, r = 0.96) are considered significantly strong, supporting their relevance in optimizing sweet pepper growth under the study's conditions. On the other hand, weaker correlations (e.g., number of fresh fruits per plant with fresh yield, r = 0.76) suggest a moderate but non-significant relationship with yield, indicating that fruit production may depend on other factors not captured by these variables. The reason for these variations lies in the complex interactions between plant physiological processes influenced by fertilizers, where specific growth parameters (like plant height and leaf number) strongly influence each other. In contrast, others (fruit number) may be subject to more varied environmental or nutritional factors. Significant correlations (r > 0.5): These parameters are closely linked, suggesting they could be important indicators for managing growth and yield in sweet pepper cultivation. Non-significant correlations (r < 0.5). These weaker relationships indicate that while these parameters are still related, they may not be the most reliable predictors for improving yield or growth independently [46].

Table 19. The correlation coefficient of biofertilizer and nano NPK fertilizer on growth and yield of sweet pepper (*Capsicum annuum*) a comparative study with granular NPK.

Parameters	Plant Height (cm)	Branch Number	Number of Leaves Plant^{-1}	Number of fresh fruits per Plant^{-1}	Weight of one Seed Plant-1	Fresh yield (g) Plant^{-1}	Fresh fruit Diameter (cm)	Shoots Weight (g)	Dry matter (g)
Plant height (cm)	1								
Branch number	0.93	1.00							
Number of leaves plant^{-1}	0.96	0.97	1.00						
Number of fresh fruit plant^{-1}	0.43	0.36	0.36	1.00					
Weight of one seed plant^{-1}	0.92	0.91	0.93	0.48	1.00				
Fresh yield (g) plant^{-1}	0.70	0.70	0.71	0.76	0.81	1.00			
Fresh fruit diameter (cm)	0.84	0.81	0.83	0.49	0.84	0.71	1.00		
Shoots weight (g)	0.74	0.76	0.72	0.45	0.77	0.69	0.77	1.00	
Dry matter (g)	0.75	0.78	0.74	0.38	0.77	0.64	0.77	0.99	1

Values in bold are different from 0 with a significance level of alpha=0.05

Conclusions

The findings of this study underscore the significant impact of fertilizer type and application method on sweet pepper growth and productivity. Foliar nano NPK and bio-fertilizers demonstrated superior effectiveness in enhancing key agronomic traits such as plant height, branch number, and fresh and dry yield compared to traditional granular NPK. These treatments promoted vigorous vegetative development and efficient nutrient assimilation, which collectively contributed to higher productivity. The consistent performance of nano and bio-fertilizers suggests they may enhance nutrient uptake mechanisms or stimulate plant physiological activity more effectively than conventional approaches.

Moreover, the study reveals that moderate application levels yield the most beneficial outcomes, as higher concentrations did not result in further performance improvements. This points to the importance of optimizing fertilizer dosage to balance efficacy with resource use. The positive correlations among growth parameters further affirm the holistic advantages of nano and bio-based treatments. These findings not only highlight the potential of innovative fertilizers to improve crop performance but also emphasize the need for sustainable fertilization strategies. Continued research should focus on long-term impacts, including soil health and crop quality, as well as the biochemical pathways involved in these enhanced growth responses.

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تقييم تأثير الأسمدة الحيوية والأسمدة النانوية NPK على النمو الخضري وإنتاجية الفلفل الحلو (Capsicum annuum): دراسة مقارنة مع الأسمدة الحبيبية NPK

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الخلاصة

أُجريت هذه الدراسة في معهد بكرجو التقني عام 2024 لتقييم تأثير الأسمدة المختلفة على نمو الفلفل الحلو ***(Capsicum annuum)*** ، بما في ذلك الأسمدة الورقية النانوية***NPK*** ، والأسمدة الحيوية، والأسمدة الحبيبية ***NPK*** بتراكيز (1، 1.5، و2) مل لتر$^{-1}$ للأسمدة الورقية النانوية ***NPK*** والأسمدة الحيوية، و(1، 1.5، و2) غم لتر$^{-1}$ للأسمدة الحبيبية ***.NPK*** أظهر التحليل الإحصائي باستخدام اختبار دنكن متعدد الحدود عند مستوى احتمال ***95%*** تفوق جميع مستويات الإضافة على المجموعة المقارنة او الشاهد (52.3 سم) من حيث ارتفاع النبات، حيث سجلت الأسمدة الورقية النانوية ***NPK*** (95.0 سم) والأسمدة الحيوية (93.1 سم) أعلى القيم، مما يشير إلى تعزيز قوي للنمو. ولم تسفر زيادة التراكيز عن 1 مل لتر$^{-1}$ عن تحسن ملحوظ في ارتفاع النبات، مما يعكس انخفاض الكفاءة الإنتاجية عند الجرعات الأعلى. كما كان عدد الفروع والعائد الطازج في أعلى مستوياته عند 1 مل لتر$^{-1}$، مع تفوق الأسمدة الحيوية والنانوية على الأسمدة الحبيبية***NPK*** . أظهرت جميع معاملات الإضافة زيادة كبيرة في إنتاج المادة الجافة، حيث تم تسجيل أعلى متوسط للمادة الجافة (297.2 جم) عند تركيز 1 مل لتر$^{-1}$ من الأسمدة الورقية النانوية***NPK*** ، مما يعكس كفاءتها في تعزيز النمو. كما أكد الارتباط الإيجابي بين ارتفاع النبات والصفات الخضرية، مثل عدد الفروع والأوراق، الفوائد الملحوظة للأسمدة النانوية والحيوية في تحسين الأداء النباتي. وتشير هذه النتائج إلى أن الإدارة المثلى للأسمدة، من خلال تحديد جرعات ومستويات رش مناسبة، يمكن أن تعزز بشكل فعال نمو الفلفل الحلو وإنتاجيته

كلمات مفتاحية: الفلفل حلو، سماد نانو ***NPK*** ، سماد الحيوى . سماد حبيبي ***NPK***، ***Capsicum annum L***.