Research Article

Responses of Strawberry Growth, Yield, and Marketable Fruit Quality to Mycorrhizal Inoculation, Mineral Fertilization, and Foliar Application of Chitosan

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Abstract | Two fields and storage experiments were conducted to evaluate the impact of inoculation application of mycorrhiza, mineral fertilizer, and foliar spraying of chitosan on the growth, quantity, and quality characteristics of strawberry fruits. The field experiment included 18 treatments including mycorrhiza inoculation at the concentrations (without inoculation and inoculation with mycorrhiza at a concentration of 30 g.plant^{1}) which were symbolized as B0, B1 respectively, mineral fertilizer at the concentrations of 0, 50, and 100% recommended dose fertilization for the fertilizer NPK which were symbolized as F0, F1, and F2 respectively, and foliar with chitosan at the concentrations of 0, 2.5, and 5 ml. L^{-1}, which were symbolized as C0, C1, and C2 respectively, with three replications. The storage trait was conducted using the same experimental design as the initial study, under a storing temperature of 2°C. The findings showed that treatment B1 significantly enhanced heights of plant, number of leaves, diameter of crown, number of flower clusters, yield per plant, fruit T.S.S., and vitamin C content. It also helped preserve T.S.S. and vitamin C during storage while reducing fruit deformation. Treatment F2 produced a notable increase in growth and yield traits and likewise reduced fruit distortion. Similarly, treatment C2 recorded significant improvements in the previously mentioned parameters. Furthermore, the interaction treatments B1C2, B1F2, and C2F2, along with the triple interaction B1C2F2, yielded the highest values across all evaluated parameters.

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Introduction

Fragaria ananassa Duch., a member of the Rosaceae family, is a crop of great economic significance and is widely cultivated worldwide (Xiong *et al.*, 2021). Strawberries have high nutrient demands, as the plant produces a substantial fruit yield relative to fruit size. However, the plant is prone to diseases and insect infestations, and its fruits are non-climacteric, highly perishable, and characterized by a short shelf life due to their high respiration rate and elevated water content (Barkaoui *et al.*, 2021; Pinzon *et al.*, 2020). Around 90% of land plants are capable of forming symbiotic associations with Arbuscular

Mycorrhizal Fungi (AMF), a relationship regarded as evolutionarily significant in helping plants adapt to a wide range of environmental challenges (Begum *et al*., 2019). In return for supplying AMF with photosynthetically derived carbon in the form of saccharides and lipids, plants gain access to water and essential nutrients including phosphorus, nitrogen, and micronutrients through the fungus, which employs its extensive hyphal network to explore and acquire these limited resources beyond the rhizosphere (Smith and Read 2008; Xie *et al*., 2022). Symbiotic relationships between plants and AMF have been extensively researched, with numerous benefits for plant growth being documented. These include improved uptake of water and nutrients, along with enhanced tolerance to environmental stresses such as drought, salinity, heavy metal toxicity, and extreme temperatures (Adeyemi *et al*., 2021; Haggag *et al*., 2023). Mousa *et al*. (2024) noted that the inoculation with mycorrhiza on the strawberry plant has significantly increased plant height, leaf area, root weight, dry weight of plant, and fruit weight. Abdulkadhim and Hussein (2023) recorded that the inoculation with mycorrhiza on the strawberry plant had increased plant total yield, T.S.S., and vitamin C in the fruits. Chitosan is a polysaccharide resulting from the deacetylation of chitin. This natural polymer is convenient and largely available as waste from the shells of shrimps and crabs processed by the seafood industry. It is nontoxic, biocompatible, biodegradable, antimicrobial, and antioxidant, due to the presence of free amine groups and hydroxyl groups to scavenge free radicals to form stable micro molecular radicals (Tamer *et al*., 2020). The positive effect of Chitosan on metabolism and increased photosynthesis, which enhanced plant growth (Gornik *et al*., 2008, Mondal *et al*., 2012). When applied to horticultural crops, it not only limits disease development before harvest but also minimizes losses caused by microbial infections during transportation and postharvest storage. (Malerba and Cerana 2018; Sakif *et al*., 2016; Saniewska 2001). It demonstrates strong antifungal activity against various pathogens, particularly gray mold, a major factor responsible for strawberry deterioration and postharvest decay (Sharma *et al*., 2009). Ramteke *et al*. (2023) mentioned that the pre-harvesting application of chitosan on grape trees improves fruit quality and extends shelf life. Vandana *et al*. (2023) found that chitosan foliar application at the concentrations of 2, 3, and 4g.l^{-1} on the growth of the Strawberry plant; concentration of 4g.l^{-1} recorded the highest leaf number, plant height, fruit length, fruit diameter, T.S.S, Total fruit production, plant^{-1}, and extends shelf life. Macronutrients are vital for plant existence since they execute multiple metabolic activities (Tariq *et al*., 2023). Nitrogen, phosphorus, and potassium are major macronutrients (Daramola and Hatzell, 2023). Plants require particular nutrients to grow and thrive, including macronutrients, which are required in greater quantities, and micronutrients (Diwakar *et al*., 2023). nitrogen, phosphorous, and potassium, these macronutrients are needed in substantial amounts by plants to perform key physiological functions such as photosynthesis, respiration, and growth. Ensuring a balanced supply of these nutrients in the soil is therefore vital for healthy plant development (Karthika *et al*., 2018). In both natural ecosystems and agricultural systems, nitrogen occurs in multiple forms, including nitrate, nitrite, ammonium, and amino acids (Liu *et al*., 2023). Plants readily absorb nitrogen from diverse sources such as fertilizers, the atmosphere, water, rainfall, and even molecular nitrogen (N_2) (Mahboob *et al*., 2023). Nitrogen affects the metabolism of amino acids, and supply affects plant hormonal state, and phytohormones such as abscisic acid (ABA), indole-3-acetic acid (IAA), and cytokinins (CK) are strongly connected to nitrogen signaling (Joshi *et al*., 2023, Wevar Oller *et al*., 2023). Phosphorus is an essential nutrient for plant development, being a fundamental component in nucleic acids, membrane phospholipids, and energy-dependent metabolic processes (Herrera-Estrella *et al*., 2016) Phosphorus is an essential component of photosynthetic activity, aiding in the conversion of solar energy into chemical energy, proper plant growth, and stress tolerance (Kruse *et al*., 2005), it also promotes the rapid growth of plants and root systems(Schoumans *et al*., 2014) Potassium is considered the second most abundant nutrient in plant tissues after nitrogen (Oosterhuis *et al*., 2014), Potassium directly influences photosynthesis (Tränkner *et al*., 2018) and regulates metabolism (Cuin *et al*., 2018). Additionally, it activates more than 60 enzymes and is directly involved in protein synthesis (Sardans and Peñuelas, 2021). Potassium also facilitates the transport of nutrients from the leaves to other parts of the plant and enhances nutrient uptake (Sustr *et al*., 2019). Furthermore, it reduces water loss through transpiration by regulating the opening and closing of stomata (Andrés *et al*., 2014). Kaur *et al*. (2024) recorded an increase in leaf area, leaf number, T.S.S, firmness of fruit, total yield, and vitamin C by mineral fertilizer with NPK on strawberry plants. Devi *et al.* (2024) reported that applying 100% RDF of NPK had a significant effect on the functional quality traits of strawberries. The study found that the highest values for total soluble solids, total sugars, TSS:acidity ratio, fruit volume, fruit firmness, and shelf life were achieved under the fertigation level of 100% RDF of NPK. This research aimed to enhance both the floral and vegetative growth of strawberry plants, which in turn positively influenced the quantity, quality, and marketability of the fruits.

Materials and Methods

Field experiment

Strawberry plants of the Festival variety were cultivated in a greenhouse following an R.C.B.D. design with three replications. The experiment included three factors, each applied at three different concentrations, with mycorrhiza represented as B0, B1, for the concentrations 0, 30 g.plant^{-1}respectively. The second factor was the chitosan, which was symbolized as C0, C1, and C2 for the concentrations 0, 2.5, and 5 m.l^{-1} respectively, and mineral fertilizer (NPK) in the concentrations of 0, 50, and 100% RDF of NPK which were symbolized as F0, F1, F2 respectively. Add mineral fertilizer to the soil, and Foliar application was applied 9 times after three weeks post-planting.

Storage experiment

The experiment was conducted using an RCBD. Approximately 250 g of uniform fruits were collected from each treatment, and their T.S.S. Percentage and vitamin C content were measured. The fruits were then placed in perforated plastic containers and stored at 2 ºC. After seven days of storage, the T.S.S. and vitamin C content were reassessed.

Field experiment parameters

Height of Plants (cm)

Measured at the end of the growing season using a measuring tape, from the soil surface to the apex of the plant.

Number of Leaves (leaf. Plant^{-1})

The leaf number on the stem and side branches was calculated at the end of the growth season.

Diameter of crown (mm)

Determined at the end of the growing season using a Vernier caliper.

Number of flower clusters (Clusters. Plant^{-1}):

Counting clusters in each plant.

Yield per plant (g) :

Determined by dividing the total yield of the plants by the number of plants in each experimental unit.

Distorted fruits percent (%)

Calculated using the following formula:

Distorted fruit ratio = (Number of distorted fruits ÷ Total number of fruits) × 100

Storage experiment parameters

T.S.S. Percent

Determined using a handheld refractometer.

Vitamin C (mg. 100 g^{-1} fresh weight)

Determined according to Abbas and Abbas (1992).

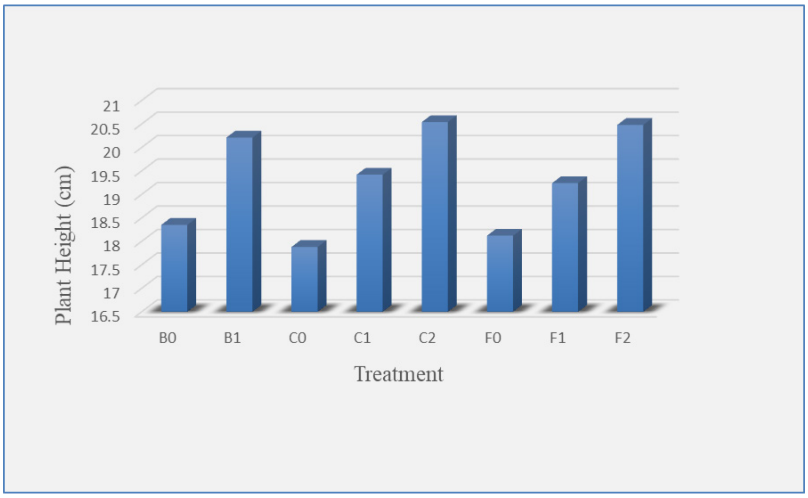

Figure 1: *Effect of Mycorrhizal inoculation (B), foliar application of chitosan (C), and mineral fertilization (F) on plant height (cm) of strawberry plants. Values are treatment means. L.S.D. (0.05): B=1.30, C= 1.60, F= 1.60.*

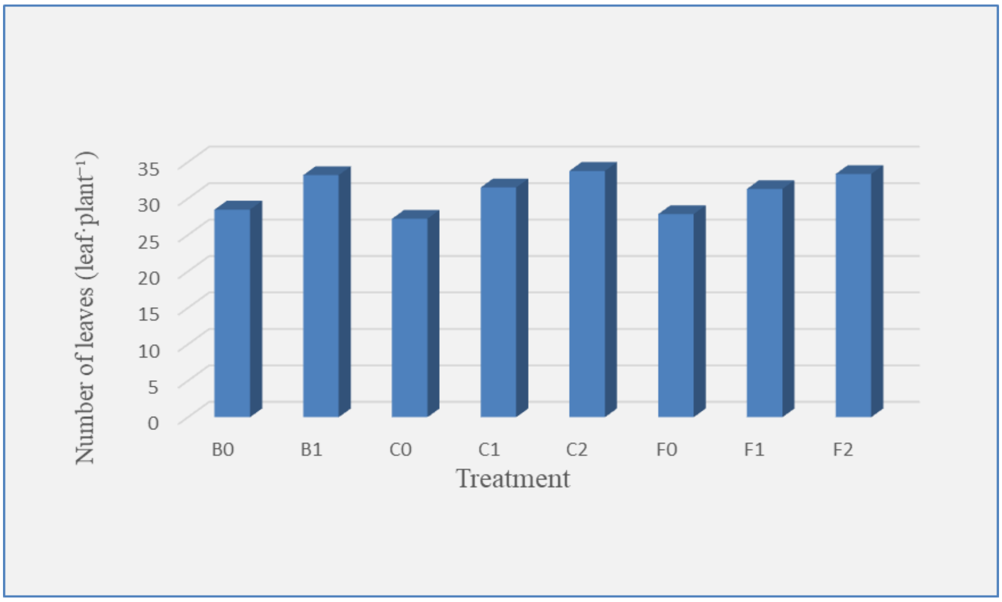

Figure 2: *Effect of Mycorrhizal inoculation (B), foliar application of chitosan (C), and mineral fertilization (F) on number of leaves (leaf plant-^{1}) of strawberry plants. Values are treatment means. L.S.D. (0.05): B=1.50, C= 1.84, F= 1.84.*

Results and Discussion

Field experiment results

Plant height (cm)

Figure 1 exhibits that the Inoculation with mycorrhiza fungi at the treatment of B1 has given a significant increment in plant height, reaching 20.21 cm, in comparison with B0, which has given the lowest value, at 18.35 cm. Also, The Chitosan foliar application at the treatment of C2 was significantly increased values of this feature reaching 20.54 cm, compared to C0, which was 17.88 cm.and the Mineral fertilizer with NPK also showed a significant increase in plant height at the treatment of F2 which was 20.48 cm as compared to F0, which was 18.12 cm. The bi-interaction between the study factors also affected the above-mentioned parameter, as the treatment of B1C2 has given the highest value, at 21.67 cm, if compared to B0C0, which has given 17.19 cm. The interaction treatment B1F2 resulted in the greatest plant height, reaching 21.36 cm, compared to 17.02 cm in B0F0. Similarly, the C2F2 interaction produced the highest plant height of 21.58 cm, whereas C0F0 recorded 16.24 cm. The triple interaction of all studied factors had the most pronounced effect, with B1C2F2 achieving the tallest plants at 22.85 cm, compared to the lowest value of 14.81 cm in B0C0F0.

Leaves number (leaf. Plant^{-1})

The results presented in Figure 2 indicate that number of leaves was significantly increased when mycorrhizal inoculation applied, with treatment B1 showing the highest value of 33.21 leaves per plant compared to B0, which had 28.48 leaves per plant. Similarly, foliar application of chitosan in treatment C2 significantly enhanced leaf number, reaching 33.79 leaves per plant, while C0 recorded 27.23 leaves per plant. Application of mineral fertilizer (NPK) in treatment F2 also resulted in a significant increase, reaching 33.37 leaves per plant compared to 27.86 leaves per plant in F0. Furthermore, the dual interaction between mycorrhiza and chitosan in treatment B1C2 produced the highest leaf number, peaking at 36.49 leaves per plant, which was significantly higher than B0C0, recorded at 24.50 leaves per plant. Also, the interaction treatment of B1F2 gave the highest value of the studied parameter, reaching 35.48 leaves. Plant^{-1} compared to B0F0, which produced 24.81 leaves per plant. Additionally, the interaction treatment C2F2 showed the highest leaf number, at 35.64 leaves per plant, compared to C0F0, which had 22.86 leaves per plant. The tri-interaction among the studied factors exhibited the greatest increase in leaf number, with treatment B1C2F2 reaching 38.44 leaves per plant, whereas B0C0F0 recorded the lowest value of 18.17 leaves per plant.

Diameter of crown (mm)

Figure 3 shows a significant increase in the diameter of strawberries crown under the mycorrhizal Inoculation of the treatment of B1, reaching 24.88 mm, compared to the control treatment B0, which

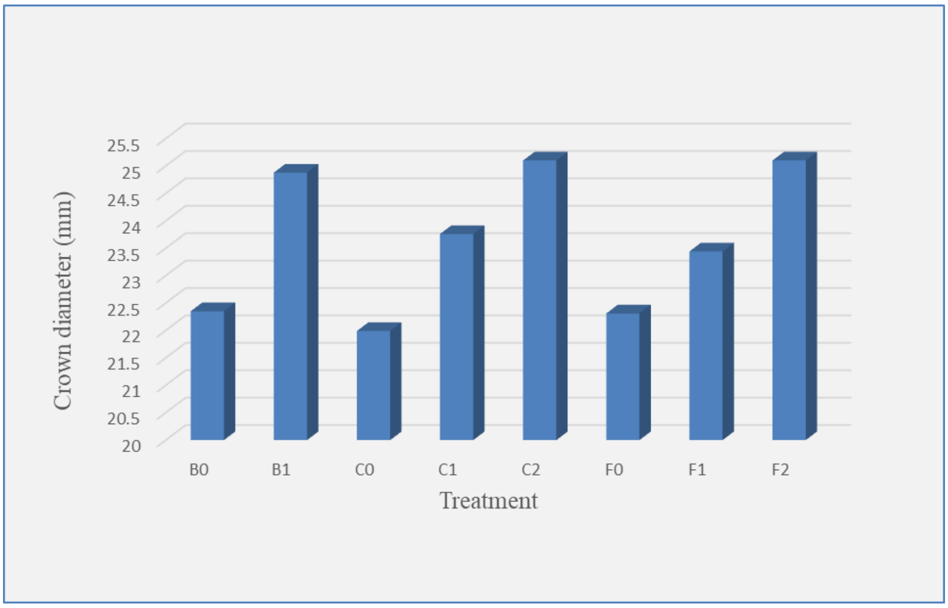

Figure 3: *Effect of Mycorrhizal inoculation (B), foliar application of chitosan (C), and mineral fertilization (F) on crown diameter (mm) of strawberry plants. Values are treatment means. L.S.D. (0.05): B=1.32, C= 1.62, F= 1.62.*

recorded the lowest crown diameter of 22.35 mm, the results show that foliar application of chitosan in treatment C2 significantly increased this parameter, reaching 25.10 mm, while C0 recorded 21.99 mm. Similarly, the application of mineral fertilizer (NPK) in treatment F2 led to a notable increase in crown diameter, reaching 25.10 mm compared to 22.31 mm in F0. Additionally, the dual interaction of factors in treatment B1C2 produced the highest crown diameter of 26.76 mm, whereas B0C0 recorded the lowest value of 20.99 mm. The B1F2 treatment also achieved a high crown diameter of 26.46 mm, compared to 21.02 mm in B0F0. Likewise, C2F2 recorded the highest crown diameter at 26.23 mm, versus 20.01 mm in C0F0. Furthermore, the triple interaction in treatment B1C2F2 resulted in the maximum crown diameter of 27.89 mm, while B0C0F0 showed the lowest value at 18.76 mm.

The increased vegetative growth indicators, such as plant height, leaves number, and crown diameter, resulting from the influence of mycorrhizal fungi, are attributed to the positive role of the symbiotic relationship between these fungi and plant roots. This relationship promotes root colonization and spore formation in the soil. This symbiosis enhances the uptake and accumulation of essential nutrients, particularly phosphorus, through the ability of the fungal hyphae to extract phosphorus from soil particles and transport it to the plant roots. Furthermore, mycorrhizal fungi contribute to improving the root zone environment by strengthening soil structure, increasing soil stability, and enhancing water retention and aeration, thus creating favorable conditions for plant growth and the proliferation of beneficial microorganisms. Moreover, mycorrhizal fungal hyphae extend beyond the root drainage zones, increasing the effective root surface area and promoting the uptake of water and a wide range of nutrients, including nitrogen, potassium, calcium, magnesium, and micronutrients. Association with mycorrhizal fungi improves plant physiological performance by enhancing photosynthetic efficiency and chlorophyll content, and by stimulating the synthesis of growth-regulating substances such as auxins and cytokinin's, which promote cell division and elongation. Furthermore, mycorrhizal fungi improve nutrient utilization efficiency and increase plant tolerance to abiotic stresses such as drought and nutrient deficiencies, ultimately leading to more vigorous vegetative growth and improved soil water relations (Velasquez *et al*., 2020; Aslanpour *et al*.,2019; Rodriguez and Sanders, 2015). Additionally, the mycorrhizae may secrete phosphatase enzymes and organic acids such as carbonic acid (H_2CO_3), which dissolve in water and lower soil pH, thereby increasing the availability of nutrients, especially phosphorus, for plant uptake. Phosphatase enzymes also help convert unavailable organic phosphorus into a readily absorbable mineral form. As a result, the plant receives a greater supply of essential nutrients, particularly the macronutrients nitrogen, phosphorus, and potassium, which are critical for plant growth. This positively reflects on the plant's metabolic activities and leads to an overall improvement and enhancement of its growth characteristics (Javeria *et al*., 2017; Parihar *et al*., 2020) These results are in agreement with (Hzaa *et al*., 2024) on strawberry, and with (Arıkan *et al*., 2023) on strawberry and with (Fadel *et al*., 2024) on soybean and with (Al-Khafaji and Al-jubouri, 2024) on carrot. The effects of chitosan are attributed to its ability to enhance photosynthesis, which positively impacts vegetative growth indicators, leading to increased plant height, leaves number, and crown diameter. Furthermore, chitosan improves nutrient utilization efficiency by enhancing the uptake of macro- and micronutrients and reducing their loss, thus supporting vegetative growth. Chitosan also influences the levels of plant growth regulators, such as gibberellic acid and cytokinin, which play a key role in promoting cell division and elongation (Rekso, 2005). (Hidangmaiyom *et al*. 2019) reported that spraying chitosan on leaves stimulates photosynthesis through a mechanism that regulates stomata opening and closing, thereby improving gas exchange and photosynthetic efficiency. Chitosan also promotes the production of antioxidant enzymes and stimulates the synthesis of organic acids, amino acids, sugars, and other metabolic compounds essential for growth. Additionally, chitosan contributes to strengthening cell walls, activating metabolic processes, and increasing the production of proteins and enzymes necessary for plant growth. In addition, chitosan improves the plant's ability to withstand various abiotic stresses, such as drought and nutrient deficiencies, ultimately leading to stronger vegetative growth and improved soil moisture. This result is in agreement with (AL-Malikshah and Abdulrasool, 2024) on potato, and with (Alaa El-Den and Khadr, 2023) on onion, and with (Fu *et al*., 2023; Metwaly *et al*., 2023) on strawberry. The effect of mineral fertilizer (NPK) in increasing the studied traits may be attributed to the direct addition of these elements, which led to an increase in the macronutrient content and contributed to creating a nutritional balance within the plant, resulting in enhanced cell division and elongation. Also, when present in the required amounts, they enable the plant to efficiently carry out various physiological activities, ultimately leading to improved vegetative growth (Al-Sahhaf 1989). As for the role of Nitrogen is involved in the synthesis of the amino acid tryptophan, which is the precursor to produce auxins that play a direct role in cell division and elongation and enlargement, as well as the formation of new cells ultimately boosting the vegetative growth parameters of the plant (Khan *et al*., 2009; Martin 2012). For the Phosphorus, it plays an important role in enzymatic reactions related to the synthesis of vital compounds and enhances the plant's ability to perform photosynthesis. It is a component of several enzymes, coenzymes, and high-energy compounds such as adenosine triphosphate (ATP), which is crucial for the photosynthetic process (Mattos *et al*., 2010). In addition, maintaining an adequate level of potassium is essential for numerous metabolic processes in the plant, as it is a vital macronutrient directly influenced by photosynthesis (Tränkner *et al*., 2018) and metabolic processes control (Cuin *et al*., 2018). It also facilitates the transport of nutrients from the leaves to the roots and enhances nutrient uptake (Sustr *et al*., 2019) which was reflected on the vegetative growth, these results were in confirmed previously by (Ali *et al*., 2023) on Cauliflower and (Saaseea and Al-a'amry, 2024) on potato and (Aljubori *et al*, 2024) on grape and (Shilan and Hama, 2024) on rapeseed and (Vian and Aziz, 2024) on *Gundelia rosea*, and (Omer and Mahmood, 2024) on flaxseed, and (Hameed and Khalil, 2023) on Damask Rose. Additionally, the effects observed in the dual and triple interactions may result from the individual contributions of each factor to the studied parameters, with these roles being similarly expressed in their combined interactions.

Number of flower clusters (clusters. Plant^{-1})

Table 1 shows the significant increase in the parameters studied under the mycorrhizal Inoculation at the treatment of B1, It recorded the highest value of 11.40 clusters per plant, compared to B0, which had the lowest value of 9.23 clusters per plant. Similarly, foliar application of chitosan significantly enhanced this parameter, with treatment C2 reaching 11.48 clusters per plant, while C0 recorded 8.98 clusters per plant. Also, the mineral fertilizer with NPK in the treatment of F2 significantly increased the number, reaching 11.70 clusters. Plant-1 compared with F0, which was recorded with 9.12 clusters. Plant-1. The dual interaction in treatment B1C2 produced the highest number of clusters, reaching 12.49 clusters per plant, compared to 7.92 clusters per plant in B0C0. Similarly, treatment B1F2 recorded 12.78 clusters per plant, whereas B0F0 had 8.04 clusters per plant. The C2F2 interaction also achieved the highest value for the parameter studied, with 12.57 clusters per plant, compared to 7.24 clusters per plant in C0F0. Moreover, the triple interaction in treatment

B1C2F2 showed the greatest increase, reaching 13.72

Table 1: *Effect of inoculation with mycorrhiza, mineral fertilizer and foliar application with chitosan and the interaction among them on number of flower clusters (cluster. plant^{-1}) of strawberry.*

B g.P^{-1}	C ml. L^{-1}	F_0-0	F%RDF F_1-50	F_2-100	B*C
	C_0-0	5.84	8.30	9.61	7.92
B_0-0	C_1-2.5	8.42	8.68	10.83	9.31
	C_2-5	9.85	10.17	11.42	10.48
	C_0-0	8.64	9.74	11.75	10.04
B_1-30	C_1-2.5	10.58	11.59	12.86	11.67
	C_2-5	11.39	12.34	13.72	12.49
	LSD 0.05		1.56		0.90
	B*F	F_0	F_1	F_2	B
	B_0	8.04	9.05	10.62	9.23
	B_1	10.20	11.22	12.78	11.40
	LSD 0.05		0.90		0.52
	C*F	F_0	F_1	F_2	C
	C_0	7.24	9.02	10.68	8.98
	C_1	9.50	10.13	11.84	10.49
	C_2	10.62	11.26	12.57	11.48
	LSD 0.05		1.10		0.63
		F_0	F_1	F_2	
		9.12	10.14	11.70	
	LSD 0.05		0.63		

Table 2: *Effect of inoculation with mycorrhiza, mineral fertilizer and foliar application with chitosan and the interaction among them on yield per plant(g) of strawberry.*

B g.P^{-1}	C ml. L^{-1}	F_0-0	F%RDF F_1-50	F_2-100	B*C
	C_0-0	204.73	285.78	327.35	272.63
B_0-0	C_1-2.5	290.88	324.89	384.60	333.45
	C_2-5	355.63	383.90	440.09	393.20
	C_0-0	300.61	345.24	398.32	348.05
B_1-30	C_1-2.5	369.44	403.71	455.08	409.41
	C_2-5	422.61	500.53	560.20	494.44
	LSD 0.05		41.01		23.68
	B*F	F_0	F_1	F_2	B
	B_0	281.00	330.69	383.02	331.57
	B_1	362.74	414.29	469.31	415.44
	LSD 0.05		23.68		13.67
	C*F	F_0	F_1	F_2	C
	C_0	250.81	315.30	362.41	309.50
	C_1	329.33	363.50	419.11	370.64
	C_2	388.69	440.74	499.08	442.83
	LSD 0.05		29.00		16.74
		F_0	F_1	F_2	
		322.94	373.18	426.86	
	LSD 0.05		16.74		

clusters per plant, while B0C0F0 recorded the lowest value of 5.84 clusters per plant.

Table 3: *Effect of inoculation with mycorrhiza, mineral fertilizer and foliar application with chitosan and the interaction between them on fruits distortion percent (%).*

B $g.P^{-1}$	C ml. L-1	F_0-0	F%RDF F_1-50	F_2-100	B*C
	C_0-0	17.69	14.49	14.58	15.59
B_0-0	C_1-2.5	13.58	13.30	12.36	13.08
	C_2-5	12.60	12.54	12.49	12.54
	C_0-0	14.65	13.39	13.53	13.85
B_1-30	C_1-2.5	12.26	12.06	12.59	12.30
	C_2-5	11.69	11.35	10.26	11.10
	LSD 0.05		1.83		1.05
	B*F	F_0	F_1	F_2	B
	B_0	14.62	13.44	13.14	13.74
	B_1	12.86	12.27	12.12	12.42
	LSD 0.05		1.05		0.61
	C*F	F_0	F_1	F_2	C
	C_0	16.17	13.94	14.05	14.72
	C_1	12.92	12.68	12.47	12.69
	C_2	12.15	11.94	11.37	11.82
	LSD 0.05		1.29		0.74
		F_0	F_1	F_2	
		13.74	12.85	12.63	
	LSD 0.05		0.74		

Yield per plant(g)

The results presented in Table 2 indicate that inoculation with mycorrhiza B1 significantly increased plant yield, reaching 415.44 g compared to B0, which recorded 331.57 g. Similarly, foliar application of chitosan in treatment C2 significantly enhanced yield, reaching 442.83 g, whereas the control C0 recorded the lowest value of 309.50 g. Application of mineral fertilizer (NPK) in treatment F2 also significantly improved plant yield, reaching 426.86 g compared to 322.94 g in F0. Regarding interaction effects, the dual treatment B1C2 produced the highest yield of 494.44 g, compared to the control B0C0, which recorded 272.63 g. Likewise, B1F2 achieved 469.31 g, while B0F0 recorded 281.00 g. In the interaction between chitosan and mineral fertilizer, C2F2 reached the highest yield of 499.08 g, compared to 250.81 g in C0F0. The triple interaction of all studied factors, B1C2F2, resulted in the most substantial increase, achieving 560.20 g, whereas the control B0C0F0 recorded the lowest yield of 204.73 g.

Fruits distortion percent (%)

The results presented in Table 3 indicate that inoculation with mycorrhiza B1 significantly reduced fruit distortion to 12.42%, compared to B0, which recorded 13.74%. Foliar application of chitosan also showed a significant effect, with treatment C2 recording the lowest distortion at 11.82%, significantly lower than the control C0 at 14.72%. Similarly, mineral fertilizer application in treatment F2 reduced distortion to 12.63%, compared with 13.74% in F0. Bi interactions further enhanced this effect. The combination of mycorrhiza and chitosan B1C2 recorded the lowest fruit distortion at 11.10%, compared to 15.59% in B0C0. The interaction B1F2 reduced distortion to 12.12%, compared to 14.62% in B0F0, while C2F2 showed a reduction to 11.37% versus 16.17% in C0F0.

The tri-interaction among the studied factors resulted in the most pronounced decrease in fruit distortion across treatments. Specifically, B1C2F2 recorded the lowest distortion at 10.26%, compared to the control B0C0F0, which had the highest distortion at 17.69%.

The increase in plant yield resulting from mycorrhizal inoculation may be attributed to its positive effects on vegetative growth, nutrient accumulation, and carbohydrate production, leading to an increased number of flower clusters and a higher overall yield. Mycorrhizal fungi enhance the uptake of essential nutrients such as nitrogen, phosphorus, iron, zinc, and copper, and improve hormonal balance by influencing auxin and cytokinin production, thus supporting normal fruit development and reducing distortion Percent (Rocozou *et al*., 2021). They also improve root activity and effective surface area, enhance photosynthetic efficiency, and increase plant resistance to environmental stresses, ultimately resulting in increased yield and improved fruit quality. These results agree with (Haghshenas *et al*., 2024; Mousa *et al*., 2024) on strawberry. The effect of chitosan foliar spraying on increasing the number of flower clusters is attributed to its role in enhancing the concentration of mineral nutrients within the plant. The positive effects of chitosan contribute to improved vegetative growth indicators, leading to stronger and healthier plants, and consequently, improved flower development characteristics, including an increased number of clusters. Furthermore, chitosan promotes carbohydrate accumulation in the plant by enhancing photosynthetic efficiency, increasing nutrient availability, and boosting overall plant nutrition. This leads to increased nutrient accumulation in the fruit, resulting in greater fruit weight and diameter, and thus positively impacting the overall plant yield (Faqir *et al*., 2021; Walid, 2016). Chitosan also improves fruit firmness, strengthens cell wall structure, and regulates the expression of enzymes involved in ethylene production and cell wall degradation, contributing to reduced fruit deformation. Furthermore, chitosan enhances the plant's ability to withstand environmental stresses, such as drought and nutrient deficiencies, and improves disease resistance by stimulating the production of secondary metabolites and antioxidants, ultimately leading to improved fruit quality. (He *et al*., 2018). These results agree with (Ochmian *et al*., 2022; Vandana *et al*., 2023) on strawberry. The significant increase in flowering and yield indicators resulting from mineral fertilization with nitrogen, phosphorus, and potassium can be attributed to the essential role of these nutrients in promoting vegetative growth, as evidenced by the studied traits (Figure 1, 2, and 3). This improvement led to increased photosynthetic efficiency, a higher rate of carbon uptake, and greater accumulation of synthesized nutrients, which were subsequently translocated to meet the plant's growth and development needs. This resulted in an increased number of flowering branches and a positive impact on plant yield (Bentamra *et al*., 2023). Nitrogen plays a crucial role in chlorophyll and protein synthesis, thus promoting vegetative growth, which positively impacts plant yield. Phosphorus contributes to energy transfer and the synthesis of high-energy compounds necessary for flowering and fruit set. Potassium directly affects photosynthesis (Trankner *et al*., 2018), regulates metabolic processes (Hasanuzzaman, *et al*., 2018), and promotes cell expansion (Prado, 2021), collectively leading to an increased number of branches and improved yield. Furthermore, fertilization with nitrogen, phosphorus, and potassium improves the nutritional status of the plant and stimulates the production of nucleic acids and plant hormones such as auxins and cytokinins, which promotes cell division and elongation, ultimately improving fruit growth and reducing the occurrence of deformities (Bai *et al*., 2023). These findings are consistent with those reported by (Ali *et al*., 2023, Kaur *et al*., 2024) on strawberry. Furthermore, the increases observed in the dual and triple interactions can be attributed to the individual effects of each factor on enhancing these parameters, as well as the combined behavior of the factors when interacting with one another.

Table 4: *Effect of inoculation with mycorrhiza, mineral fertilizer and foliar application with chitosan and the interaction among them on the Total Soluble Solids T.S.S (%) of the strawberry.*

B g.P^{-1}	C ml. L^{-1}	F_0-0	F%RDF F_1-50	F_2-100	B*C
	C_0-0	6.56	7.40	7.75	7.24
B_0-0	C_1-2.5	7.33	7.62	7.87	7.61
	C_2-5	7.72	7.96	7.13	7.60
	C_0-0	7.92	7.67	7.82	7.80
B_1-30	C_1-2.5	7.72	7.88	8.60	8.07
	C_2-5	8.49	8.67	8.86	8.67
	LSD 0.05		1.46		0.80
	B*F	F_0	F_1	F_2	B
	B_0	7.20	7.66	7.58	7.48
	B_1	8.04	8.07	8.42	8.18
	LSD 0.05		0.80		0.42
	C*F	F_0	F_1	F_2	C
	C_0	7.24	7.54	7.79	7.52
	C_1	7.52	7.75	8.23	7.84
	C_2	8.11	8.32	7.99	8.14
	LSD 0.05		1.01		0.53
		F_0	F_1	F_2	
		7.62	7.87	8.00	
	LSD 0.05		N.S		

Total soluble solids T.S.S (%):

The results presented in Table 4 indicate that inoculation with mycorrhiza significantly increased the T.S.S. percentage, with treatment B1 reaching 8.18% compared to 7.48% in B0. Foliar application of chitosan in treatment C2 also resulted in the highest T.S.S., reaching 8.14%, whereas C0 recorded 7.52%. Mineral fertilizer (NPK) in treatment F2 showed a slight, non-significant increase, reaching 8.00% compared to 7.62% in F0. Regarding dual interactions, treatment B1C2 achieved the highest T.S.S. at 8.67%, compared to 7.24% in the control B0C0, while B1F2 reached 8.42% versus 7.20% in B0F0. The C2F1 interaction also recorded the highest T.S.S. of 8.32%, compared to 7.24% in C0F0. The triple interaction of all factors, B1C2F2, showed the most significant increase, reaching 8.86%, whereas the lowest value of 6.56% was observed in B0C0F0.

Table 5: *Effect of inoculation with mycorrhiza, mineral fertilizer and foliar application with chitosan and the interaction between them on Vitamin C Content (mg. 100 g^{-1} fresh weight).*

B g.P^{-1}	C ml. L	-1 F_0-0	F%RDF F_1-50	F_2-100	B*C
	C_0-0	46.78	51.51	53.35	50.54
B_0-0	C_1-2.5	51.62	53.64	54.48	53.24
	C_2-5	53.42	54.76	55.90	54.69
	C_0-0	52.67	55.15	55.51	54.44
B_1-30	C_1-2.5	56.77	56.45	57.68	56.96
	C_2-5	57.74	58.45	59.65	58.61
LSD 0.05			5.79		3.34
B*F		F_0	F_1	F_2	B
B_0		50.60	53.30	54.58	52.83
B_1		55.72	56.68	57.61	56.67
LSD 0.05			3.34		1.93
C*F		F_0	F_1	F_2	C
C_0		49.72	53.33	54.43	52.49
C_1		54.19	55.04	56.08	55.10
C_2		55.58	56.60	57.78	56.65
LSD 0.05			4.09		2.36
		F_0	F_1	F_2	
		53.16	54.99	56.09	
LSD 0.05			2.36		

Vitamin C Content (mg. 100 g^{-1} fresh weight)

The results presented in Table 5 indicate that inoculation with mycorrhiza significantly increased the fruit vitamin C content, with treatment B1 recording the highest value of 56.67 mg per 100 g fresh weight, compared to B0, which had the lowest value of 52.83 mg per 100 g fresh weight. Similarly, foliar application of chitosan significantly enhanced this parameter, as treatment C2 achieved the highest vitamin C content of 56.65 mg per 100 g fresh weight, whereas C0 recorded the lowest value of 52.49 mg per 100 g fresh weight. Also, the mineral fertilizer with NPK recorded a significant value at the treatment of F2, reaching 56.09 mg. 100 g^{-1} fresh weight, compared with F0, which recorded 53.16 mg.100 g^{-1} fresh weight. The results of the dual interaction in treatment B1C2 showed the highest vitamin C content, reaching 58.61 mg per 100 g, compared to the control B0C0, which recorded 50.54 mg per 100 g. Similarly, treatment B1F2 reached 57.61 mg per 100 g, while B0F0 recorded 50.60 mg per 100 g. In the interaction between chitosan and mineral fertilizer, C2F2 achieved the highest value of 57.48 mg per 100 g, compared to 49.71 mg per 100 g in C0F0. The triple interaction of all studied factors resulted in the most significant increase, with treatment B1C2F2 recording 59.65 mg per 100 g fresh weight, whereas B0C0F0 had the lowest value of 46.78 mg per 100 g fresh weight.

Table 6: *Effect of inoculation with mycorrhiza, mineral fertilizer and foliar application with chitosan and the interaction among them on the Total Soluble Solids T.S.S (%) of the strawberry after7 days of storage at a temperature of 2°C.*

B g.P^{-1}	C ml. L	-1 F_0-0	F%RDF F_1-50	F_2-100	B*C
	C_0-0	6.94	7.07	7.20	7.07
B_0-0	C_1-2.5	7.21	7.28	7.34	7.28
	C_2-5	7.33	7.43	7.51	7.42
	C_0-0	7.59	7.66	7.72	7.66
B_1-30	C_1-2.5	7.74	7.83	8.29	7.95
	C_2-5	8.37	8.48	8.59	8.48
LSD 0.05			0.40		0.23
B*F		F_0	F_1	F_2	B
B_0		7.16	7.26	7.35	7.26
B_1		7.90	7.99	8.20	8.03
LSD 0.05			0.23		0.13
C*F		F_0	F_1	F_2	C
C_0		7.26	7.37	7.46	7.36
C_1		7.47	7.56	7.81	7.71
C_2		7.85	7.96	8.05	7.96
LSD 0.05			0.28		0.16
		F_0	F_1	F_2	
		7.53	7.63	7.78	

	LSD 0.05	0.16	

Table 7: *Effect of inoculation with mycorrhiza, mineral fertilizer and foliar application with chitosan and the interaction among them on the Content of Vitamin C (mg. 100 gm^{-1} wet weight) of the strawberry fruits after 7 days of storage at a temperature of 2°C.*

B g.P^{-1}	C ml. L^{-1}	F_0-0	F%RDF F_1-50	F_2-100	B*C
	C_0-0	40.77	44.61	47.27	44.22
B_0-0	C_1-2.5	45.71	46.82	47.93	46.82
	C_2-5	48.30	48.69	49.17	48.72
	C_0-0	45.67	46.54	47.94	46.72
B_1-30	C_1-2.5	47.45	48.59	49.90	48.65
	C_2-5	49.60	51.40	54.66	51.89
LSD 0.05			5.95		3.43
B*F		F_0	F_1	F_2	B
B_0		44.93	46.71	48.12	46.59
B_1		47.57	48.84	50.83	49.08
LSD 0.05			3.43		1.98
C*F		F_0	F_1	F_2	C
C_0		43.22	45.58	47.60	45.47
C_1		46.58	47.70	48.91	47.73
C_2		48.95	50.05	51.91	50.30
LSD 0.05			4.20		2.42
		F_0	F_1	F_2	
		46.25	47.78	49.48	
LSD 0.05			2.42		

The results in Table 6 and Table 7 show that strawberry fruits maintained their T.S.S. percentage and vitamin C content after 7 days of storage when treated with mycorrhiza, mineral fertilizer, chitosan foliar application, and their interactions. Inoculation with mycorrhiza (B1) resulted in T.S.S. and vitamin C values of 8.03% and 49.08 mg per 100 g fresh weight, respectively, compared to B0, which recorded 7.26% and 46.59 mg per 100 g fresh weight. Similarly, foliar application of chitosan in treatment C2 maintained T.S.S. and vitamin C at 7.96% and 50.30 mg per 100 g fresh weight, respectively, compared to C0, which recorded 7.36% and 45.47 mg per 100 g fresh weight. Also, the mineral fertilizer with NPK which recorded a significant value of T.S.S% and Vitamin C content at the treatment of F2 which recorded 7.78% and 49.48 mg. 100 g^{-1} fresh weight respectively compared to F0 reaching 7.53% and46.25 mg. 100 g^{-1} fresh weight respectively. As well, the storage temperature is one of the most important factors that determine the validity period and availability of the fruits after storage (Nguyen and Nguyen, 2021).

Fruits from plants inoculated with mycorrhizal fungi exhibited higher total soluble solids and vitamin C content. This is attributed to the mycorrhizal fungi's active role in enhancing the absorption of macro- and micronutrients, particularly phosphorus and potassium, improving hormonal balance within the plant, and increasing photosynthetic efficiency. These effects stimulate root system growth and enhance nutrient uptake, leading to improved synthesis and translocation of photosynthetic products to the fruit. Furthermore, mycorrhizal fungi improve nutrient and water utilization efficiency and reduce environmental stress, positively contributing to sugar accumulation and vitamin C biosynthesis, thus enhancing the nutritional value and overall quality of the fruit. These results are in agreement with (Haghshenas *et al*., 2024; Pérez-Moncada *et al*., 2024) on strawberry. Also, the effect of chitosan on the quality characteristics of strawberry fruits can be attributed to the ability of chitosan to reduce the respiration rate in fruits, which in turn decreases the consumption of sugars and organic acids, leading to their accumulation. Additionally, chitosan enhances fruit firmness by increasing lignin content and improving the structure of the cell wall, thereby contributing to the preservation of fruit quality and reducing the loss of vitamin C due to oxidation (He *et al*., 2018; Rahimi *et al*., 2018) These results are in agreement with (Fu *et al*., 2023; Metwaly *et al*., 2023) on strawberry, and with (Kumarihami *et al*., 2021) on Kiwifruit, As for the effect of NPK fertilizer on increasing the total soluble solids (TSS) and vitamin C content in fruits, it may be attributed to the role of nitrogen in enhancing vegetative growth and increasing the plant's photosynthetic capacity, which leads to a higher production of carbohydrates that are stored in the fruits as sugars. Phosphorus contributes to the formation of energy compounds within the plant, which improves the photosynthesis process and sugar storage, and also enhances the synthesis of vitamin C. Potassium, on the other hand, improves the translocation of sugars from the leaves to the fruits and strengthens fruit firmness by enhancing the structure of cell walls, which helps maintain fruit quality and reduces vitamin C loss due to oxidation (Madaiah *et al*., 2018) These results are in agreement with (Djoko *et al*., 2024) on strawberry and with (Aljubori *et al*., 2024) on grape.

Conclusions and Recommendations

Inoculation of strawberry plants with mycorrhiza and foliar application of chitosan and fertilization with mineral fertilizer (NPK), whether applied individually or in combination significantly improved most of the vegetative and reproductive growth traits. These treatments enhanced plant efficiency, promoted better growth, increased yield quantity and contributed to maintaining Postharvest fruit quality.

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Novelty Statement

The individual treatment factors and their interactions, whether dual or triple, showed significant differences in most of the traits studied. The interaction between mycorrhiza, chitosan, and mineral fertilizer (NPK) under treatment B1C2F2 resulted in the best values for all the studied traits.

Author's Contribution

Yasir. R. Khairi: The experiment, data collection, and manuscript preparation were all done
Ahmed T. Joody: Supervised the study and provided directions for the data analysis.

Generative AI and AI-assisted technology statement
The artificial intelligence analysis of all sections of this manuscript showed that none of the texts plagiarized and was with a score of zero.

Conflict of interest
The authors of this manuscript declare that they have no conflict of interest and no material or moral harm to the research institutions

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