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EFFECT OF FOLIAR APPLICATION OF BORON ACID AND CHITOSAN ON STRAWBERRY BIOACTIVE COMPOUNDS

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Abstract

This study was carried out to determine the effects of foliar application of boric acid and chitosan on yield components, fruit quality and bioactive compounds of strawberry (*Fragaria × ananassa Duch.*) (cv. Festival) plant. The study was carried out in soilless agriculture conditions in Sandıklı district of Afyon province, and boric acid and chitosan applications were carried out at different concentrations (2, 3 and 4 mg L^{-1}). The treatments showed statistically significant effects on the number of fruits per plant, yield and average fruit weight ($p<0.05$). The highest yield (569.97 g plant) and fruit number (18.83 plants) were obtained from 3 mg L^{-1} chitosan application, while higher doses (4 mg L^{-1}) caused a slight decrease in yield. Fruit firmness, soluble solids (SSC) and titratable acidity values were also increased, especially at medium boron and high chitosan concentrations. The highest SSC (8.11%) and ascorbic acid (85.67 mg 100 g^{-1}) contents were determined in the 4 mg L^{-1} chitosan application. Additionally, 3 mg L^{-1} chitosan dose significantly increased anthocyanin accumulation in fruits (78.46 mg 100 g^{-1}). Boron applications supported fruit sugar content and textural durability. Correlation analysis revealed a strong positive relationship between fruit number and yield ($r = 0.70$), and a high positive relationship between SSC and vitamin C ($r = 0.72$). PCA analysis revealed that the first two components explained 63.5% of the total variance, with chitosan applications being associated with quality parameters, while boron applications were associated with yield components. In conclusion, foliar application of boron and chitosan can be considered an effective strategy for sustainable production by increasing both yield and functional quality in strawberry.

Key words: Strawberry, boron, chitosan, bioactive compounds, antioxidant capacity, PCA

Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) is one of the most consumed berries worldwide and stands out for its high economic value and rich content of functional compounds. Strawberry fruits are rich in ascorbic acid, phenolic compounds (flavonoids, anthocyanins, ellagitannins), and organic acids (Giampieri *et al.,* 2012; Battino *et al.,* 2016). There is evidence that the antioxidant capacity of these bioactive compounds plays a role in the prevention of cardiovascular diseases, the reduction of inflammation, and the control of metabolic syndrome (Giampieri *et al.,* 2015; Unal *et al*., 2023; Unal & Okatan, 2023). However, the amount and profile of bioactive compounds in strawberry fruits are significantly influenced by genotype, growing conditions, nutritional status, environmental stress factors, and applied agronomic interventions (Aaby *et al.,* 2012). Therefore, increasing fruit bioactive compounds through sustainable production strategies is a critical goal to support both commercial quality and consumer health.

On the other hand, chitosan (chitosan) is a biodegradable polysaccharide derived from chitin. In recent years, it has received widespread attention as a biostimulant and elicitor in sustainable agriculture (Romanazzi *et al.,* 2018). Chitosan can increase the synthesis of phenolic compounds and anthocyanins by activating the phenylpropanoid pathway in plants and also stimulates antioxidant enzyme activities (SOD, CAT, POD) (Rahman *et al.,* 2018). Foliar applications of chitosan to strawberry have increased yield and increased ascorbic acid, total phenolics, and anthocyanin contents. Postharvest chitosan coatings have been reported to extend fruit shelf life (Petriccione *et al.,* 2015; Metwaly *et al.,* 2023). Thus, chitosan is considered an environmentally friendly application tool that improves strawberry quality both in the field and during marketing.

Boron (B), a micronutrient, plays an important role in fundamental physiological processes in plants, such as cell wall structure and plasma membrane stability, carbohydrate transport, pollen viability, and fertilization (Brown & Shelp, 1997; Vera-Maldonado *et al.,* 2024). B deficiency leads to yield and quality losses, especially in

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reproductive tissues. In fast-growing species such as strawberry, foliar application of B has been found to be effective in increasing tissue B concentrations and improving fruit set (Leon-Chang & Bryla, 2024). Recent reviews emphasize that boron applications positively affect quality parameters such as fruit firmness, sugar/acid ratio, and color, and may also be related to phenolic metabolism (Álvarez-Herrera *et al.,* 2025). These findings suggest that boric acid applications may increase not only yield but also functional quality in strawberry.

The combined application of boron and chitosan may potentially produce synergistic effects by activating different biological mechanisms. Considering the role of boron in cell wall and membrane stability and the elicitor effects of chitosan, it is anticipated that an increase in bioactive compounds such as total phenolics, anthocyanins, and ascorbic acid may be achieved in strawberry. However, studies directly examining the effects of combined foliar applications of boron and chitosan on strawberry bioactive compounds are limited in the literature. Therefore, demonstrating the effectiveness of this application in improving fruit quality and functional compounds will be a significant contribution from both scientific and practical perspectives (Balal *et al.,* 2017; Kluczka *et al.,* 2018; Özkaya *et al.,* 2021).

Although the existing literature has demonstrated the positive effects of boron and chitosan applications on quality parameters and bioactive compounds in strawberry fruit (Petriccione *et al.,* 2015; Rahman *et al*., 2018; Metwaly *et al.,* 2023; Álvarez-Herrera *et al.,* 2025), studies evaluating the holistic effect of combined foliar application of these two agents on the bioactive profile of strawberry fruit are quite limited. As sustainable quality improvement strategies gain increasing importance in strawberry production, the combination of boron's critical roles in nutrition and cell structure and chitosan's elicitor properties may create a potential synergy. The unique contribution of this study is to comparatively reveal the effects of single and combined foliar applications of boric acid and chitosan on total phenolic compounds, anthocyanins, ascorbic acid, and antioxidant capacity in strawberry fruit, thus providing a new perspective on both scientific knowledge and sustainable agricultural techniques that producers can implement.

Material and Method

The study was carried out in 2024 within a commercial greenhouse specialized in soilless cultivation, situated in the Sandıklı district of Afyon, Türkiye. Seedlings (cv. Festival) were obtained from a private supplier in Antalya. The young plants were established in cocopeat-filled grow bags (100 × 15 × 7 cm) placed on benches 75 cm above ground level, at a planting density of 14.2 plants per square meter. Boric acid was first dissolved in hot water, cooled to room temperature, and subsequently applied to the plant samples. A stock solution of chitosan (2% w/v) was prepared by dissolving it in 0.5% (v/v) glacial acetic acid under continuous stirring, after which the pH was adjusted to 5.6 using 1 N NaOH. The solution was then sterilized at 121°C for 20 minutes, and lower concentrations (e.g., 5 mg/L) were obtained by appropriate dilution with distilled water. The prepared solutions were applied via foliar spray when the first flowering was observed. The second application was made 15 days after the first application.

Yield components: Fruit number per plant was recorded, and the total yield (g) was determined based on the cumulative weight of fully ripened fruits (characterized by complete red coloration) harvested during the growing period.

Physical characteristics: For physical trait evaluation, 20 fruits were randomly sampled from each replicate at harvest. Mean fruit weight (g) was obtained by dividing the total fruit mass by the corresponding fruit count per plant. Fruit length (L, cm) and diameter (D, cm) were measured using a Vernier caliper, whereas fruit firmness (kg cm^{-2}) was assessed with a penetrometer.

Strawberry fruit quality: A set of 10 randomly selected, fully matured fruits was collected from each treatment plot to assess fruit quality characteristics according to AOAC protocols (Anon., 2012). The measurement of soluble solid contents (SSC) was performed with a digital refractometer (Leica Abbe model). The concentration of ascorbic acid (vitamin C) was expressed as mg per 100 g of fresh weight and quantified by titration using 2,6-dichlorophenolindophenol as the indicator. Fruit juice acidity (AC) was evaluated through titration with 0.1 N NaOH until reaching pH 8.1, and the results were reported as citric acid percentage. Total sugars (TS) in fresh strawberry samples were determined following the Lane and Eynon procedure. Anthocyanin (ANTHO) content was analyzed spectrophotometrically using 1.5 N HCl.

Results and Discussions

Number of fruits per plant, yield per plant, fruit width and fruit length values are presented in Fig. 1. Boron and chitosan applications significantly affected the number of fruits per plant ($p<0.05$). The average fruit number in the control group was determined as 15.30 pieces/plant. Boron applications, especially at the doses of 2 mg L^{-1} (17.87) and 3 mg L^{-1} (17.57), increased the number of fruits and were statistically located in Group ab. The 4 mg L^{-1} boron application decreased the value to 16.80 and was found in Group b. Among the chitosan applications, the 3 mg L^{-1} dose provided the highest number of fruits (18.83 pieces/plant) (Group a), whereas the 4 mg L^{-1} dose (14.60) gave the lowest value (Group c). This result showed that high chitosan doses might negatively affect fruit set.

Boron and chitosan applications also significantly increased the yield values per plant ($p<0.05$). Yield was determined as 415.83 g/plant in the control group. Boron doses of 2 mg L^{-1} (562.47 g) and 3 mg L^{-1} (560.60 g) produced the highest yield values (ab group), while 4 mg L^{-1} dose was in bc group with 533.37 g. A similar trend was observed in chitosan applications. 2 mg L^{-1} (551.73 g) and 3 mg L^{-1} (569.97 g) doses significantly increased the yield (ab–a groups), while 4 mg L^{-1} dose decreased to 517.13 g in group c. The findings showed that both boron and chitosan applications at appropriate doses had a yield-enhancing effect, but high doses might give partially negative results.

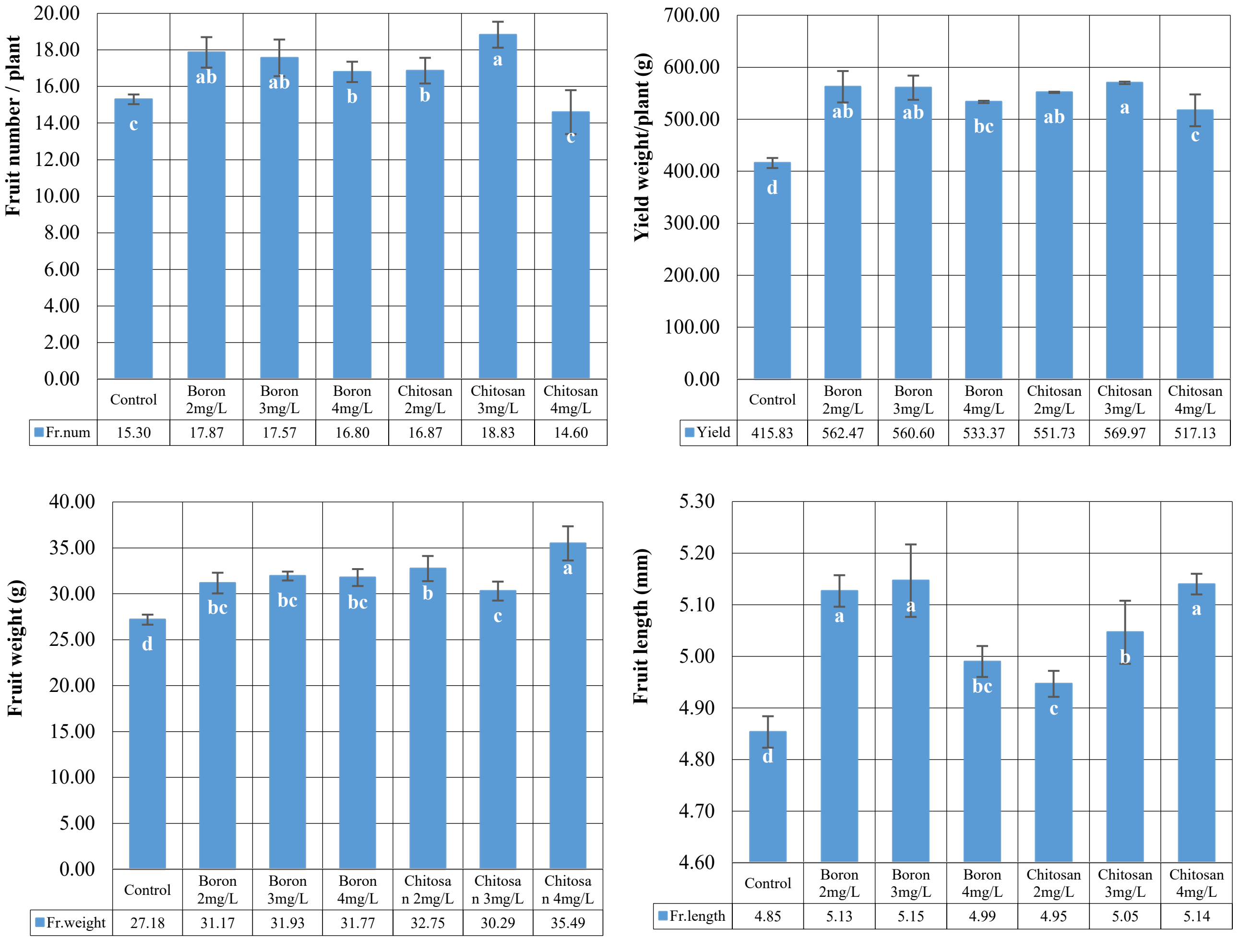

Fig. 1. Number of fruits per plant, yield per plant, fruit width and fruit length values.

Boron and chitosan applications also caused significant increases in fruit weight ($p<0.05$). The average fruit weight in the control group was determined as 27.18 g. Boron applications increased fruit weight; 2 mg L^{-1} (31.17 g) and 3 mg L^{-1} (31.93 g) doses were in the bc group, and 4 mg L^{-1} (31.77 g) dose was in the bc group. In chitosan applications, 2 mg L^{-1} (32.75 g) and 4 mg L^{-1} (35.49 g) doses provided higher fruit weights and were found in letter groups b and a, respectively. In particular, the 4 mg L^{-1} chitosan dose increased the weight per fruit to the highest level, providing an approximately 30% increase compared to the control group. This supports the fact that chitosan is an effective biostimulant in fruit growth and development.

When fruit length values were examined, it was observed that both boron and chitosan applications had significant effects ($p < 0.05$). The average fruit length in the control group was determined to be 4.85 mm. The 2 mg L^{-1} (5.13 mm) and 3 mg L^{-1} (5.15 mm) boron applications reached the highest values and were in Group a. In contrast, the 4 mg L^{-1} boron dose was found in Group bc with a value of 4.99 mm. In chitosan applications, the 3 mg L^{-1} (5.05 mm) and 4 mg L^{-1} (5.14 mm) doses showed significant increases compared to the control group (Groups b–a). These results suggested that optimum levels of boron and chitosan applications supported fruit development, while higher doses might have a partially restrictive effect.

Boron and chitosan applications resulted in significant improvements in all yield and quality parameters studied. Moderate doses (2–3 mg L^{-1}) in particular showed the highest performance for most parameters. Chitosan applications generally produced slightly higher yield and fruit quality values compared to boron applications. This can be explained by chitosan's ability to increase cell wall strength, enhance photosynthetic activity, and reduce physiological stress. Consequently, the use of boron and chitosan at appropriate doses can be considered an effective approach for improving fruit yield and quality.

Fruit firmness, SSC and titratable acidity values are presented in Fig. 2. Boron and chitosan applications affected fruit firmness values statistically significantly ($p<0.05$). Fruit firmness was determined as 1.39 kg/cm² in the control group. Hardness values were increased as a result of boron applications; 2 mg L^{-1} (1.68), 3 mg L^{-1} (1.76) and 4 mg L^{-1} (1.84) doses showed higher hardness compared to the control group. This increase showed that boron increased textural strength by supporting pectin calcification playing a role in cell wall structure. Chitosan applications also produced similar positive effects. Hardness values at doses of 2 mg L^{-1} (1.73), 3 mg L^{-1} (1.83) and 4 mg L^{-1} (1.76) were found to be significantly higher than the control group. Particularly, 3 mg L^{-1} chitosan application provided the highest hardness and this could be explained by chitosan delaying water loss and softening by forming a film layer on the fruit surface.

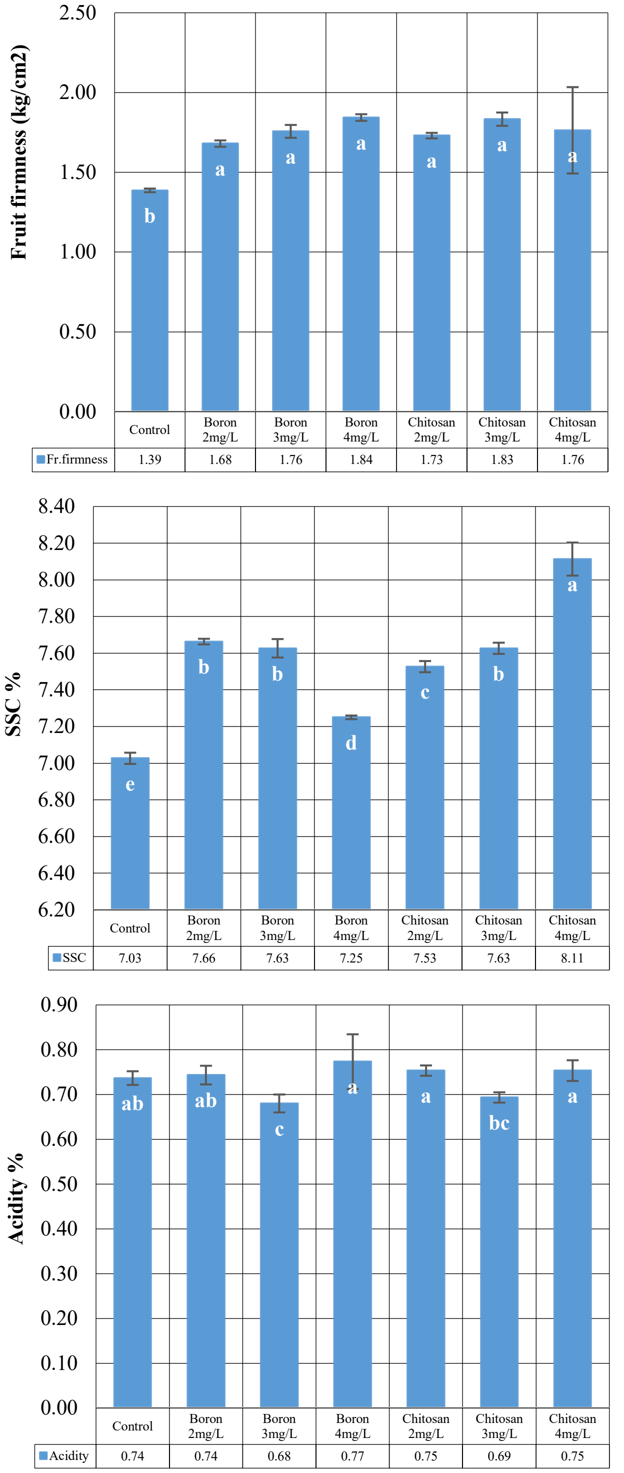

Fig. 2. Fruit firmness, SSC and titratable acidity values.

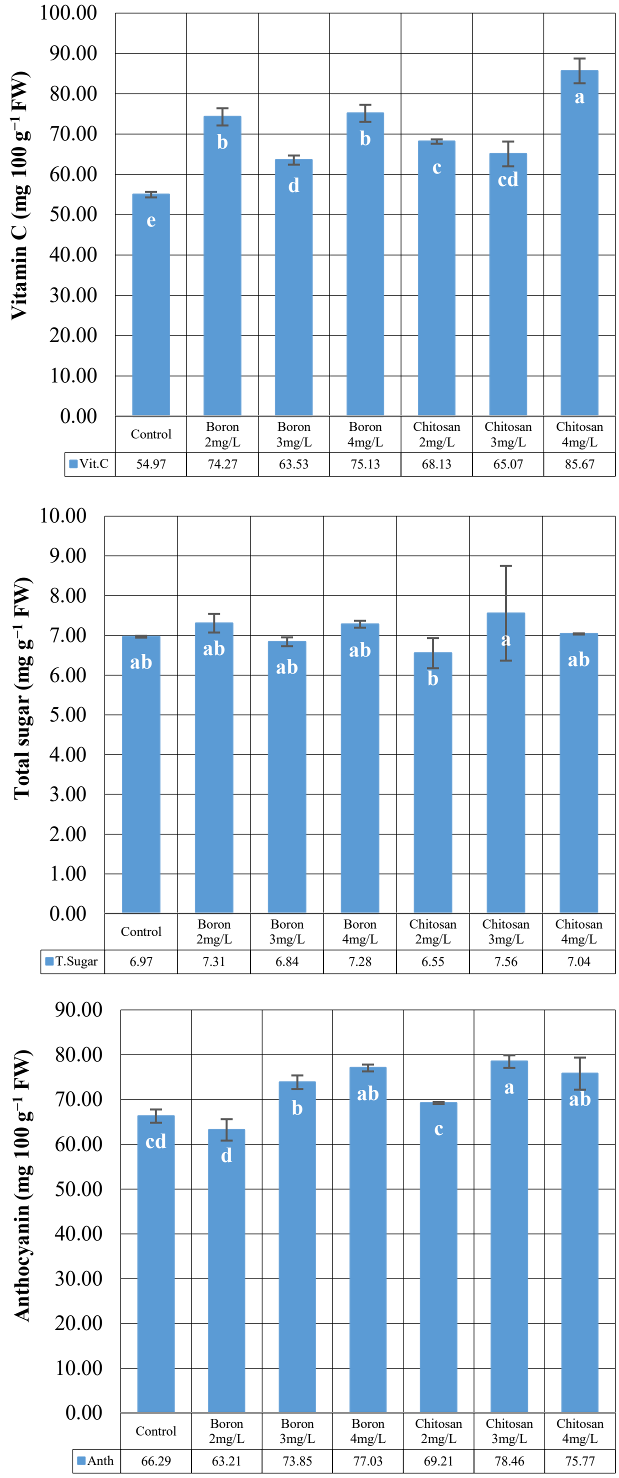

Fig. 3. Vitamin C, total sugar and total anthocyanin values.

Boron and chitosan applications affected the SSC ratio of fruits statistically significantly ($p<0.05$). The SSC value was determined as 7.03% in the control group. In boron applications, SSC values were increased at 2 mg L^{-1} (7.66%) and 3 mg L^{-1} (7.63%) doses (group b), and decreased to 7.25% in 4 mg L^{-1} boron application (group d). Chitosan applications generally increased the SSC ratio. 2 mg L^{-1} (7.53%) and 3 mg L^{-1} (7.63%) doses provided moderate increases, while the highest value was obtained at 4 mg L^{-1} (8.11%) application (group a). These results indicated that chitosan promoted carbohydrate metabolism and sugar accumulation, while high doses of boron may cause a partial decrease by affecting the osmotic balance.

Titratable acidity values of fruits were affected by both boron and chitosan applications ($p<0.05$). Acidity was determined as 0.74% in the control group. In boron applications, acidity values remained relatively constant at 2 mg L^{-1} (0.74%) and 3 mg L^{-1} (0.68%) doses, while they reached the highest level of 0.77% in the 4 mg L^{-1} boron application (group a). When chitosan applications were examined, it was seen that the 2 mg L^{-1} (0.75%) and 4 mg L^{-1} (0.75%) doses were similar to the control group, while the 3 mg L^{-1} (0.69%) dose showed lower values (group bc). These findings suggested that high boron doses could promote organic acid synthesis, while chitosan could cause a partial decrease in acid levels by reducing respiration rate at certain doses.

Vitamin-C, total sugar and total anthocyanin values are presented in Fig. 3. Boron and chitosan applications significantly affected the vitamin C content of fruits ($p<0.05$). In the control group, ascorbic acid content was determined as 54.97 mg 100 g^{-1}. Boron applications increased the amount of vitamin-C; the highest values were obtained at 2 mg L^{-1} (74.27) and 4 mg L^{-1} (75.13) doses (group b). In contrast, 3 mg L^{-1} boron application gave a lower result of 63.53 mg 100 g^{-1} (group d). The increase was more pronounced in chitosan applications. While the 2 mg L^{-1} (68.13) and 3 mg L^{-1} (65.07) doses were found to be higher than the control group, the 4 mg L^{-1} chitosan application provided the highest ascorbic acid content with 85.67 mg 100 g^{-1} (group a). These findings indicate that chitosan strengthens antioxidant defenses in plants and promotes ascorbic acid accumulation. It can also be said that boron supports vitamin-C metabolism when applied at optimal levels.

Boron and chitosan applications showed significant effects on total sugar content ($p<0.05$). Total sugar content was determined as 6.97 mg g^{-1} in the control group. Boron applications generally increased the total sugar content; no statistically significant difference was found between the 2 mg L^{-1} (7.31), 3 mg L^{-1} (6.84) and 4 mg L^{-1} (7.28) doses (group ab). In chitosan applications, the 3 mg L^{-1} (7.56 mg g^{-1}) dose provided the highest sugar content (group a), while the 2 mg L^{-1} (6.55) dose showed the lowest value (group b). This increase can be explained by the fact that chitosan accelerates carbohydrate synthesis by increasing photosynthetic efficiency. The results reveal that chitosan application promotes sugar accumulation, especially at medium doses.

Boron and chitosan applications also significantly affected the anthocyanin content in fruits ($p<0.05$). Anthocyanin amount was determined as 68.29 mg 100 g^{-1} in the control group. Boron applications increased anthocyanin accumulation; the highest values were given at 3 mg L^{-1} (73.85) and 4 mg L^{-1} (77.03) doses (groups b–ab). Chitosan applications provided a stronger increase. A significant difference was seen between the 2 mg L^{-1} (69.21) and 3 mg L^{-1} (78.46) doses, especially the 3 mg L^{-1} chitosan application produced the highest anthocyanin content (group a). The 4 mg L^{-1} (75.77) dose also remained at a high level (group ab). These results suggested that chitosan promoted anthocyanin synthesis by stimulating phenylpropanoid metabolism. Furthermore, boron may indirectly promote pigment formation by increasing structural stability.

Boron and chitosan applications caused significant changes in the biochemical composition of the fruits. The highest vitamin C value was obtained from the chitosan 4 mg L^{-1} application. The chitosan 3 mg L^{-1} dose was the most prominent in terms of total sugars. Anthocyanin content was found to be highest in both the boron 4 mg L^{-1} and chitosan 3 mg L^{-1} applications.

These results showed that chitosan increased quality components by stimulating both primary (sugar metabolism) and secondary (phenolic compound synthesis) metabolisms in plants, while boron played a supporting role in this effect.

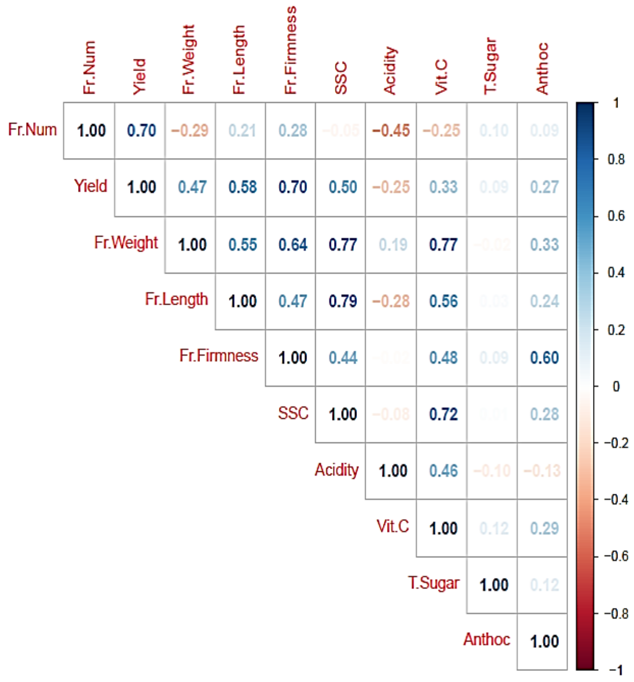

Fig. 4. Results of the correlation analysis.

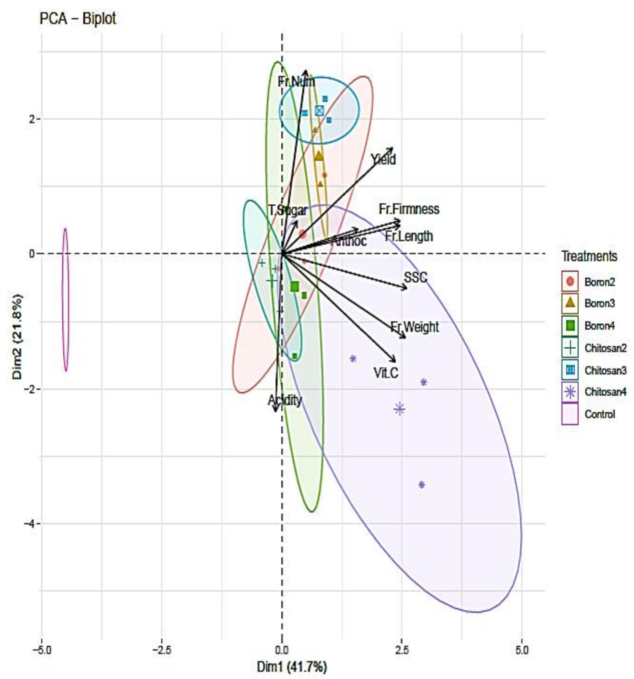

Fig. 5. Results of the principal component analysis (PCA).

The results of the Pearson correlation analysis conducted to demonstrate the relationships between the parameters are presented in Fig. 4. According to the analysis results, a strong and positive correlation ($r = 0.70$) was found between fruit number (Fr. Num) and yield (Yield). This relationship indicates that increasing the number of fruits per plant directly affects total yield. Similarly, high positive correlations were found between fruit weight (Fr. Weight) and fruit length (Fr. Length) ($r = 0.64$), and SSC (soluble solids in water) ($r = 0.77$). This suggests that larger and longer fruits also have higher sugar content. Moderate positive correlations were found between fruit firmness (Fr. Firmness) and SSC ($r = 0.44$)

and vitamin-C (r = 0.48). This finding suggests that firmer fruits may also have higher ascorbic acid content. However, a strong positive correlation was also found between SSC and vitamin C (r = 0.72). This suggests that both components increase simultaneously as maturity increases. When negative correlations were examined, weak to moderate inverse correlations were found between SSC and fruit number (r = -0.05) and yield (r = -0.50). This suggests that increasing fruit number may partially dilute total dry matter accumulation. Overall, the correlation matrix reveals compensatory relationships between yield components and quality parameters.

The PCA results, performed to holistically evaluate the relationships between morphological, physical, and chemical parameters of fruit, are presented in Fig. 5. As a result of the analysis, the first two principal components explained 63.5% of the total variance (PC1: 41.7%, PC2: 21.8%). PC1 showed particularly high positive loadings with quality parameters such as fruit weight, fruit length, firmness, SSC, and vitamin-C. PC2 was more closely associated with yield components such as fruit number, yield, and total sugars. Significant differences were observed among the treatments in the biplot plot. Chitosan 3 and 4 mg L^{-1} applications were located in the lower right region and showed positive correlations with vitamin C, SSC, fruit weight, and anthocyanin variables. This suggests that higher chitosan doses significantly increased quality parameters. Boron 2 and 3 mg L^{-1} applications were located in the center right of the plot and exhibited close correlations with fruit number and yield variables. The control group was clearly separated from the other treatments, with a low quality-yield combination, located in the lower left region. These results demonstrated that PCA analysis could clearly differentiate the plant responses of boron and chitosan treatments, with chitosan treatments exhibiting superior performance in quality parameters.

When the correlation and PCA results are evaluated together, it was observed that boron and chitosan applications had complementary effects on fruit yield and quality traits. Boron applications were more effective on yield and fruit number, while chitosan applications enhanced quality indicators such as phenolic compounds, ascorbic acid, SSC, and anthocyanin contents. These findings suggest that both compounds, when used together or in sequential applications at appropriate doses, can have a synergistic effect on fruit quality and productivity.

Discussion

This study investigated the effects of boric acid and chitosan applications on yield components, physical and chemical quality traits, and bioactive compounds of strawberry (*Fragaria* × *ananassa* Duch.), and revealed synergistic or complementary effects of these two agents. The findings showed that both compounds significantly improved both yield and functional quality in strawberry plants. These results supported the use of boron and chitosan together in sustainable production strategies. According to the results obtained in the study, chitosan applications caused significant increases in fruit number, fruit weight, SSC (water-soluble solids), vitamin C, and anthocyanin contents. In particular, the 3 mg L^{-1} chitosan dose showed the highest performance in terms of yield (569.97 g plant) and anthocyanin content (78.46 mg 100 g^{-1}). These findings suggested that the biostimulant effect of chitosan is dose-dependent.

Chitosan acts as an "elicitor" that activates defense mechanisms in plant tissues. When detected by receptors in the plant cell membrane, it triggers signal transduction pathways (specifically jasmonate, salicylic acid, and ethylene pathways) and activates phenylpropanoid metabolism (Romanazzi *et al.,* 2018). This mechanism results in increased phenylalanine ammonia lyase (PAL), polyphenol oxidase (PPO), and peroxidase (POD) activities, which in turn accelerate the synthesis of flavonoids, anthocyanins, and phenolic compounds (Rahman *et al.,* 2018).

In this study, a significant increase in ascorbic acid and anthocyanin levels was observed following chitosan application. Similarly, Metwaly *et al*., (2023) reported that chitosan application increased phenolic content and antioxidant capacity in strawberries, while also maintaining fruit firmness and prolonging quality. Chitosan also reportedly reduces transpiration loss by forming a thin film on the leaf surface, thus preserving water-holding capacity and cell turgor in the fruit (Fouda *et al*., 2022). This supports the increased fruit firmness and SSC values obtained in the study.

Chitosan also supports primary metabolism by increasing carbon fixation and photosynthetic activity in plant metabolism. The increase in photosynthetic products accelerates the accumulation of sucrose and glucose in the fruit, increasing total sugar content. This, in turn, led to an increase in SSC of up to 8.11%. These results demonstrate that chitosan is a physiological regulator that indirectly affects not only quality but also yield.

The primary function of boron in plants is to maintain cell wall integrity and support plasma membrane stability (Brown & Shelp, 1997; Riaz *et al.,* 2021). This study demonstrated that boron had particularly pronounced effects on fruit firmness, fruit number, and yield. The highest yield (560–562 g $plant^{-1}$) and fruit number (17–18 fruit/plant) values were obtained at boric acid doses of 2–3 mg L^{-1}.

These findings are consistent with reports by Leon-Chang & Bryla (2024) that boron increases pollen viability and fertilization success during flowering. In the presence of sufficient boron, cross-linking of rhamnogalacturonan-II complexes in the cell wall occurs, which increases tissue strength. Indeed, the study observed that boron treatments increased fruit firmness by up to 30% compared to the control group.

Boron is also known to facilitate the transport of photosynthetic products into fruit tissues during fruit development due to its role in carbohydrate transport (Ganie *et al.,* 2013; Vera-Maldonado *et al.,* 2024). This mechanism is consistent with the increase in total sugar content (7.31 mg g^{-1}) in the study. However, the fact that high boron concentration (4 mg L^{-1}) caused a partial decrease in some quality parameters points to the element's narrow-range toxicity. Excess boron can cause metabolic stress by causing permeability disorders and osmotic imbalances in the cell membrane (García-Sánchez *et al.,* 2020; Álvarez-Herrera *et al.,* 2025).

In the study, parallel increases were observed in quality parameters such as vitamin-C, anthocyanins, SSC, and total sugar following boron and chitosan applications. The high positive correlation between these components (e.g., vitamin C–SSC: r = 0.72) suggests that fruit ripeness and antioxidant capacity improve concurrently.

Ascorbic acid synthesis occurs via L-galacturonic acid in plants. Application of chitosan promotes ascorbic acid accumulation by increasing ascorbate peroxidase activity. Chitosan also slows the oxidative degradation of ascorbic acid by controlling reactive oxygen species (ROS) (Gómez-García & Ochoa-Alejo, 2016; Rahman *et al.,* 2018).

Boron, on the other hand, indirectly contributes to phenolic metabolism by maintaining intracellular redox balance. This explains the increased vitamin C and anthocyanin levels in boron applications. In particular, the anthocyanin content reached 77.03 mg/100 g/day at a boron dose of 4 mg L^{-1}, indicating that boron indirectly supports phenylpropanoid pathways.

These results indicate that the combined use of chitosan and boron simultaneously stimulates both primary metabolism (carbohydrate accumulation) and secondary metabolism (phenolic synthesis). This enhances both the sensory quality (flavor, color, aroma) and functional quality (antioxidant capacity, contribution to human health) of strawberries.

Conclusion

This study comprehensively demonstrated the effects of foliar application of boric acid and chitosan on the yield, quality, and bioactive compounds of strawberry (*Fragaria × ananassa* Duch.). The findings indicate that both compounds provided significant improvements in both productivity and functional quality in strawberry production. Chitosan applications particularly enhanced fruit quality by increasing fruit number, fruit weight, SSC, ascorbic acid, and anthocyanin contents. Chitosan doses of 3–4 mg L^{-1} provided high biochemical quality by activating phenylpropanoid metabolism and antioxidant defense systems. Boron applications, on the other hand, strengthened cell wall stability and supported fruit firmness, yield, and sugar accumulation. Optimum boron doses of 2–3 mg L^{-1} were determined. Correlation and PCA analyses revealed strong relationships between chitosan and quality parameters, while boron showed strong relationships with yield components. These results suggest that the two agents, applied together or sequentially, can produce complementary and synergistic effects. Overall, foliar applications of boron and chitosan at appropriate doses offer a sustainable, environmentally friendly, and high-value-added production model for strawberry cultivation. This approach can reduce the use of chemical fertilizers and pesticides while improving fruit quality, supporting both producer income and consumer health. The findings from this study suggest that future evaluations of boron-chitosan combinations with different dose and timing strategies should be conducted, and the effects of fruit components on metabolic pathways should be investigated at the molecular level.

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