Research Article

Sustainable Apple Production with Improved Quality through Integrated Nutrient Management in High Altitude

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Abstract | The technology for producing fruits enriched with essential nutrients beneficial to human health. Due to the widespread popularity of apple cultivation in Pakistan, extensive research has been conducted. This experiment aimed to investigate the foliar application of boron (B), calcium (Ca), and silicon (Si) on the yield and quality of apple cultivars. Apple cultivars Royal Gala, Mondial Gala and Treco Gala were studied and treated with various levels of B, Ca and Si i.e. Control (water spray), T1= 0.75B + 4.50Ca+ 6.00Si (g L^{-1}), T2 = 1.50B + 9.0Ca + 12.0Si (g L^{-1}), T3 = 2.25B + 13.50Ca + 18.0Si (g L^{-1}), T4 = 3.0B + 18.0Ca + 24.0Si (g L^{-1}). All the treatment combinations were replicated three times during both years and the foliar application of B, Ca and Si of different combinations were applied to the apple cultivars at three different growth stages i.e. Pink bud stage, at 50% petal fall and ten days after fruit set. The results of the experiment revealed that foliar application of boron, calcium and silicon significantly increased yield (122.17 kg) while less infested scab fruits (1.81 %) and cracked fruits (0.55 %) were obtained. The maximum total soluble solids (15.01), fruit boron (130.59 mg kg^{-1}), fruit calcium (10.00 mg kg^{-1}) and silicon in fruits (0.32%) were recorded. The combined foliar application of boron, calcium, and silicon @ 2.25 B + 13.50 + 18.00 Si (gL^{-1}) demonstrated notable potential to enhance apple fruit yield and quality traits. Among the cultivars studied, Royal Gala showed superior performance in yield and fruit quality. Further research is needed to optimize the combined foliar application of B, Ca, and Si to achieve better yield and quality across various agro-climatic conditions.

Received | January 17, 2025; **Accepted** | March 13, 2025; **Published** | May 19, 2025
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Citation | Ahmad, I. and M. Sajid. 2025. Sustainable apple production with improved quality through integrated nutrient management in high altitude. *Sarhad Journal of Agriculture,* 41(2): 752-763.
DOI | https://dx.doi.org/10.17582/journal.sja/2025/41.2.752.763
Keywords | Apple trees, Boron, Calcium, Fruit quality, Silicon, Yield

Introduction

Apple (*Malus sylvesltris*) is one of the world's most important tree fruit (Reed *et al.*, 2024). Apple belongs to the family Rosaceae and genus Malus (Rasool *et al.*, 2024). According to Food and Agriculture Organization (FAOSTAT, 2020), apple is grown globally on 6.5 million hectares of land with production of 126 million tones. Pakistan is ranked 24th in apple production with 732300 tones and 34th largest by the area for apple production. About 80% of Pakistan's apple production is contributed by Baluchistan province, followed by Khyber Pakhtunkhwa, contributing 25% of Pakistan's total apple production (GoP, 2021). Many cultivars of apples are grown in Pakistan, including (Royal Gala, Mondial Gala, Treco Gala, Golden Delicious, Red Delicious, Spartan, Red Chief, Summer Red, Fuji, Jonica, Jona Gored, Kala Kulu, Kaja, Gacha, Amri, Mushadi and Kashmiri (Javad *et al*., 2020). Despite its significance, apple production is still below its potential capacity in Pakistan. Due to the lack of inability to provide inputs at the appropriate amount and time there is a considerable gap between the potential and the actual fruit yield. The impacts of climate change and natural disasters on agricultural production have significantly reduced the quality and quantity of products. Boron (B) has a significant impact on mitigating the negative effects of abiotic stress, boosting crop yield, and enhancing nutrient uptake. Its role in the metabolism and transport system of carbohydrates as well as in the synthesis and function of cellular integuments is vital (Banerjee *et al*., 2021; O'Neill *et al*., 2004). It also promotes the resistance of crop plants against drought stress by improving photosynthetic efficiency, hormone synthesis, sugar transport, lipid metabolism, flower retention, pollen formation, seed germination and seed yield (Michael *et al*., 2012). During chilling stress, boron application enhances photosynthetic activity and improves the activities of plant antioxidants, thus reducing the risk of oxidative stress caused by temperature. It has been reported that foliar application of boron is more effective in mitigating the negative impact of water logging on plants. Boron plays a crucial role in maintaining the integrity of cell walls, thereby improving the tolerance of plants to water logging stress. Under Boron deficiency conditions, apple fruits may also have low concentrations of soluble solids and acids (Botelho, 2020). Calcium (Ca) is a very important macronutrient, which is closely related to mediating the cell and plant development routes. It also plays a vital role in improving plant response to different stress by regulating various physiological features (Rahman *et al*., 2015). Calcium's ability to stabilize cellular membranes and serve as a signaling molecule for intracellular processes can help plants cope with these stressors and maintain their overall health and productivity (Parvin *et al*., 2019). Reactive oxygen species (ROS) can actually act as signaling molecules and help moderate stress tolerance in plants. This is done by driving the expression of stress-responsive genes that are governed by calcium signaling pathways (Mittler *et al*., 2004). Calcium deficiency in apples causes bitter pit, that start as water-soaked spots in the outer cortical flesh of the fruit, frequently just under the skin, later cell dehydration and death result in the collapse of the outermost cells, causing small dark brown depressed lesions (pits) on the surface (Nissen *et al*., 2018). Calcium is one of the most important nutrients affecting the quality of fruits, where there are many physiological symptoms associated with the lack of this element called calcium-related disorders (Wang *et al*., 2021). Research indicates that at least three sprays of calcium applied at monthly intervals starting from May or June are usually vital (Nandita *et al*., 2023). Silicon (Si) is the second most abundant element in the earth's crust after oxygen, with a percentage of 26 % (Wang *et al*., 2019). FAO reports, approximately 210-224 tons of silicon is removed from the world's agricultural soils every year because silicon-containing fertilizers are not applied to the soil and the low use of organic fertilizers, silicon soil content has decreased in a way that may affect plant production (Saleem *et al*., 2019). Silicon is a very beneficial element for plants because its deficiency causes abnormal growth, development, and reproduction (Pavlovic *et al*., 2021). Silicone improves plant defense mechanisms against environmental and biological influences and thus positively reflects the quantity and quality of the crop. Some studies have pointed at the important effects of silicon on apple trees, which increased the content of chlorophyll in leaves and increased the efficiency of photosynthesis (Bianchini *et al*., 2019). Silicon also stimulates the development of roots (Ramirez-Olvera *et al*., 2019). Silicon also reduces physiological disorders in fruit like bitter pit and fruit cracking reducing water loss from leaves and fruit (Etesami and Jeong, 2020). An experiment was conducted to confirm the usefulness of foliar fertilization of boron, calcium and silicon in apple trees. The results of this experiment will answer the question of whether foliar nutrition with different combinations of boron, calcium and silicon affects the yield and quality of apple fruit cultivars.

Materials and Methods

Plant material and study site

The experiment was conducted during two growing seasons (2022–2023) at Kalam summer station of Agriculture Research Institute Mingora Swat (35°29'12.29"N and 72°34'51.19"E). Mean weather records of monthly rainfall, maximum and minimum temperature were noted for the apple production seasons of 2022 and 2023 as presented in Table 2.

The mean monthly rainfall, maximum and minimum temperature were recorded during the experimental period (Supplementary Figure 1). In this experiment three apple cultivar (Royal Gala, Mondial Gala and Treco Gala) were used. The apple orchard was 09 years old; trees were grown on a semi-vigorous rootstock MM-111, with a semi-intensive management system, spaces at 5 × 5 m and trained on modified center leader system. The soil of the experimental site was analyzed for physic-chemical properties (Supplementary Table 1).

Treatment details and experimental design

This experiment included fifteen treatments (three apple cultivar + five treatments combination) that were evaluated for two consecutive years. The study was conducted using randomized complete block design and repeated three times. The arrangement of five treatment combinations i.e., Control (water spray), 0.75 B + 4.50 Ca+ 6.00 Si (g L^{-1}), 1.5 g L^{-1} B + 9.00 g L^{-1} Ca + 12.00 Si (g L^{-1}), 2.25 g L^{-1} B + 13.50 g L^{-1} Ca + 18.00 Si (g L^{-1}), 3.00 g L^{-1} B + 18.00 g L^{-1} Ca + 24.00 Si (g L^{-1}). The source of calcium (Ca), boron (B), and silicon (Si) were calcium chloride, boric acid, and potassium silicate, respectively.

Traits examined

According to the standard protocol the traits studied in this experiments were yield plant^{-1}, scab infected fruit and cracked fruit, total soluble solids, total sugar, reducing sugar, boron, calcium, and silicon in fruits.

Total soluble solids (°Brix)

Total soluble solids (TSS) were measured at room temperature by using portable hand held refractometer (Model ATAGO, Japan) following the method as stated by Dong *et al.* (2001).

Total sugar

Sugar content was determined according to Lane-Eynon method (Pomeranz and Meloan 2002).

Reducing sugars (%)

Reducing sugar was determined by Lane and Eynon method as described in association of official analytical chemist (AOAC, 2000).

Reducing Sugars (%) = (Correction factor (CF) x Vol (ml) made)/ (Titration reading x Vol (ml) made) x 100

Boron content in fruit

Azomethine solution method was used for B contents determination in fruits.

Calcium content in fruit

The fruit samples were weighed and oven dried at 70 °C and was weighed periodically so that weight becomes constant. After oven drying, the fruit samples were ground using tema mill. The digestion was carried out by adding 10 ml of concentrated HNO_3 and was placed for overnight. The samples were heated carefully on a hot plate until the production of red NO_2 fumes ceased. The beaker was cooled and were added a small amount (2-4 ml) of 70% $HClO_4$, were heated again. The calcium content of leaf samples was measured by the procedure described by Adrian and Stevens (1977) by using Atomic Absorption Spectrophotometer using model GBC AA 932. The spectrophotometer was calibrated with a standard solution of 5μgml^{-1}.

Silicon content in fruit

The silicic acid was determined colorimetrically by reaction with molybdate. 1-ml of the aliquot of the extract-solution was pipetted into a 50-mL plastic cup then added 19 ml distilled water. A series of standard solution was made from the diluted stock 50 mg kg^{-1}solution Take 1 ml 500 gL^{-1}HCl solution and 2 ml ammonium heptamolybdate solution was added to the samples and standards. After 5-10 minutes, 2 ml oxalic acid solution was added, and was shaken again carefully. The absorbance of blank, standards, and samples were noted on the Spectrophotometer at 410 nm wavelength. A calibration curve was made for standards, plotting absorbance against the respective Si concentration. The Silicon concentration was noted in the unknown samples from the calibration curve by using the method of (Korndorfer *et al.* 2004) and calculating by the following formula.

Statistical analysis

All data obtained from experiments was analyzed statistically according to the analysis of variance (ANOVA) procedure utilizing STATISTIX 8.1 software. Significant differences ($p \leq 0.05$) among means was identified using Fisher's least significant difference (LSD) tests at 5 % level of significance Steel *et al.* (1997).

Results and Discussion

Yield plant^{-1} (kg), scab infected fruits (%) and cracked fruit (%)

Statistical analysis of the data indicated that various combinations of nutrients (B, Ca and Si) and apple cultivars (Royal Gala, Mondial Glala and Treco Gala) have significant effects on yield plant^{-1} (Kg) of apple (Table 1). The interaction between nutrients combinations and cultivars were non-significant for yield plant^{-1} of apple. The mean data for yield plant^{-1} revealed that maximum yield plant^{-1} (122.17 Kg) was recorded in plants treated with 2.25 B + 13.5 Ca + 18.0 Si (gL^{-1}), followed by plants treated with 1.5 B + 9.0 Ca + 12.0 Si and 3.0 B + 18.0 Ca + 24.0 Si (gL^{-1}) that resulted (119.42 Kg) and (106.60 Kg) respectively, while minimum yield tree^{-1} (90.74 Kg) was noted in un-treated plants. Similarly in case of different cultivars, maximum yield plant^{-1} (110.95 Kg) was recorded in cultivar Royal Gala, followed by Mondial Gala with yield plant^{-1} (108.74 Kg) and lowest yield plant^{-1} (104.75 Kg) was found in Treco Gala.

Table 1: *Yield plant^{-1} (kg), scab infected fruits (%) and cracked fruit (%) of apple cultivars as affected by foliar application of boron, calcium and silicon in combination.*

Nutrients combinations (g L^{-1})	Studied attributes		
	Yield plant^{-1} (kg)	Scab affected fruits (%)	Cracked fruit (%)
Control (Water Spray)	90.74 e	4.42 a	2.08 a
0.75B+4.50Ca+6.0Si	101.82 d	3.65 b	1.77 b
1.50B+9.0Ca+12.0Si	119.42 b	1.86 d	0.55 d
2.25B+13.50Ca+18.0Si	122.17 a	1.81 d	0.52 d
3.0B+18.0Ca+24.0Si	106.60 c	2.43 c	0.74 c
$LSD_{0.05}$	2.53	0.09	0.06
Apple cultivars			
Royal Gala	110.95 a	2.67 c	1.04 c
Mondial Gala	108.74 b	2.79 b	1.13 b
Treco Gala	104.75 c	3.04 a	1.22 a
$LSD_{0.05}$	1.41	0.05	0.04
Years			
2022	107.8 a	2.8 a	1.1 a
2023	108.5 a	2.8 a	1.1 a
$LSD_{0.05}$	NS	NS	NS
Interactions			
T x Cv	NS	Figure 1	Figure 2
Y x Cv	NS	NS	NS
Y x T	NS	NS	NS
Y x T x Cv	NS	NS	NS

Mean values in columns followed by similar letter (s) are statistically similar at 5% level of significance. NS= Non significant.

The data pertaining scab infected fruits of apple in response to various combinations of nutrients (B, Ca and Si) and cultivars (Royal Gala, Mondial Glala and Treco Gala) are expressed in (Table 1). The statistical analysis of the mean data revealed that various nutrients combinations (B, Ca and Si) and cultivars (Royal Gala, Mondial Glala and Treco Gala) significantly (P≤ 0.05) affected scab infected fruits. The interaction between nutrients combinations and cultivars also showed significant effect (Figure 1) while, rest of the interactions were non-significant. Combined application of 2.25 B + 13.5 Ca + 18.0 Si (gL^{-1}) resulted in less (1.81 %) scab infected fruits in apple cultivars, that was statistically similar with those plants treated with 1.50 B + 9.0 Ca + 12.0 Si (gL^{-1}), which resulted in (1.86 %) scab infected fruits, followed by plants treated with 3.0 B + 18.0 Ca + 24.0 Si (gL^{-1}) and 0.75 B + 4.5 Ca + 6.0 Si (gL^{-1}), which produced (2.43 %) and (3.65 %) scab infected fruits in apple cultivars, respectively. Maximum scab infected fruits (4.42 %) were recorded in control plants. Similarly different cultivars showed significant difference for scab infected fruits (%) of apple plants. Maximum scab infected fruits (3.04 %) were recorded in Treco Gala, followed by Mondial Gala with (2.79 %) and lowest (2.67%) was found in Royal Gala.

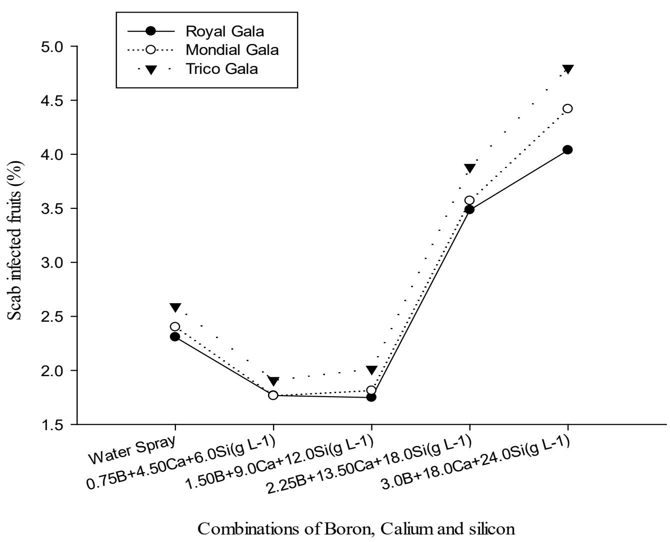

Figure 1: *Interaction between nutrients combinations (born, calcium, silicon) and apple cultivars (Royal Gala, Mondial Gala and Treco Gala) for the scab infected fruit (%) of apple cultivars.*

Cracked fruits (%) of apple cultivars were significantly (P≤0.05) affected by treatments combination of boron, calcium and silicon, and cultivars. Among the treatment combination the decrease in cracked fruit (0.52 %) was recorded in plants treated with 2.25 B + 13.50 Ca + 18.00 Si (gL^{-1}), which is statistically similar with 1.50 B + 9.00 Ca + 12.00 Si (gL^{-1}) having (0.55 %) cracked fruit, followed by cracked fruits in plants treated with 3.00 B + 18.00 Ca + 24.00 Si (gL^{-1}) (0.74 %). Control treatment produced the maximum cracked fruit (2.08 %). In case of cultivars, maximum cracked fruits were reported in Treco Gala (1.22 %) followed by Mondial Gala having cracked fruits (1.13 %). Royal Gala produced the minimum cracked fruits (1.04 %). The interaction effect of treatment combinations (T) and cultivars (Cv) was also found significant for cracked fruits (Figure 2).

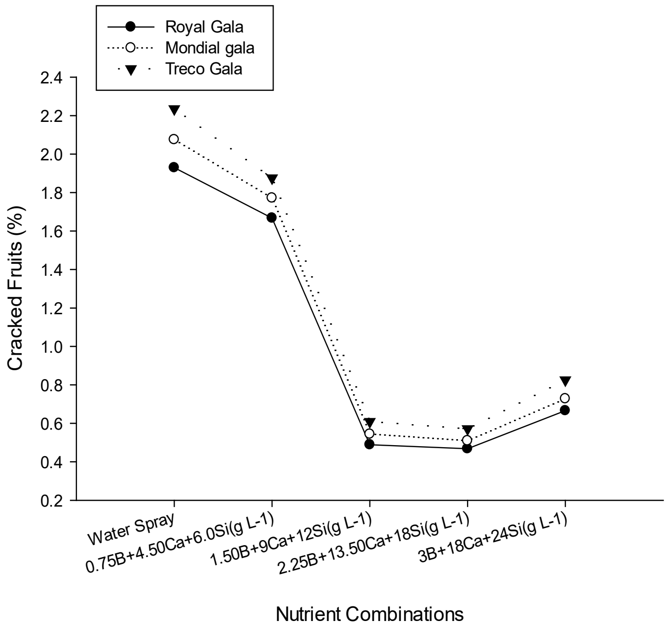

Figure 2: *Interaction between nutrients (born, calcium, silicon) and apple cultivars (Royal Gala, Mondial Gala and Treco Gala) for the cracked affected fruit (%) of apple cultivars.*

The combined application of boron, calcium, and silicon has been increasingly recognized for its potential to enhance apple yield by improving fruit quality, strengthening plant structure, and enhancing resistance to biotic and abiotic stresses. The present results are supported by the findings of Hossain *et al.* (2014), who reported that the combined application of boron and calcium significantly increased apple fruit yield and quality by improving pollination, reducing fruit drop. Similarly, Ahmad *et al.* (2022) reported that the addition of silicon to boron and calcium treatments resulted in enhanced resistance to environmental stress, leading to a significant increase in apple fruit yield under both normal and stress conditions. According to Shireen *et al.* (2018), adequate boron availability improves the flower to fruit ratio, resulting in better fruit retention and higher yield. Calcium, on the other hand, contributes to improved cell wall integrity and reducing the chances of premature fruit drop, which indirectly enhances the overall yield. A study by Kanwar and Sharma (2019) found that calcium applications reduced physiological disorders like bitter pit and fruit drop, leading to an increase in fruit production. The synergistic effect of Si with B and Ca likely supports higher productivity by improving the structural integrity of the plant and enhancing nutrient uptake. In a study by Liang *et al.* (2020), silicon application improved the water-use efficiency and nutrient absorption, leading to better yield outcomes in apple trees.

The combined application of boron, calcium, and silicon exhibited a synergistic effect in reducing scab affected fruit. The multi faceted approach of strengthening cell walls, enhancing plant defense mechanisms, and minimizing pathogen entry resulted in a notable decrease in scab incidence across all apple cultivars tested. These findings align with previous research demonstrating that the integration of these nutrients can significantly enhance disease resistance in horticultural crops (Ruemmele *et al.*, 2017). Calcium's role in cell wall fortification makes the epidermis more resistant to fungal penetration, reducing scab incidence. Similar results were obtained by Verma *et al.* (2019), who reported that calcium application reduced scab severity by up to 25% due to its ability to enhance the structural integrity of the epidermal cells. Our findings indicate that silicon application significantly reduced the percentage of scab-affected fruit in the treated cultivars, which is consistent with previous studies highlighting silicon's role in disease management (Cai *et al.*, 2008). A study by Debona *et al.* (2017) found that silicon applications could reduce fungal infections in various crops, including apples, by forming physical barriers, such as silicate layers on the epidermis, that make it difficult for pathogens to penetrate and strengthening both physical and biochemical defenses. Silicon helps reinforce plant cell walls by depositing silica in the outer layers, forming a physical barrier that reduces fungal penetration (Ma and Yamaji, 2006). The combined application of these nutrients could reduce the incidence of scab affected fruits significantly. Their synergistic action enhances both the structural defenses and immune responses of apple plants, resulting in lower scab infection rates, as corroborated by several studies (Heine *et al.*, 2020; Sun *et al.*, 2021).

Insufficient calcium leads to weakened cell walls, making the fruit more susceptible to cracking, particularly under conditions of fluctuating moisture. An investigation by Fallahi *et al.* (2018) revealed that calcium treatments significantly reduced fruit cracking in apple by maintaining fruit tissue firmness and preventing epidermal ruptures. Research suggests that regular calcium sprays during the growing season significantly reduce the incidence of apple scab and cracking (Marschner, 2012). Boron also helps in reducing fruit cracking by improving cell wall elasticity. It regulates the balance between cellular expansion and division, ensuring that fruit grows without developing internal stresses that could lead to cracking. Similar results were recorded by Wojcik and Wojcik (2017) who confirmed that boron applications reduced the rate of cracked fruit in apple trees by improving cell wall cohesion and elasticity. Silicon's role in reducing cracked fruit is linked to its ability to enhance cuticle strength and reduce water loss. Silicon has been shown to reduce transpiration rates and increase the water-holding capacity of cells, which lowers the risk of rapid cell expansion and fruit cracking. In apple plants, silicon supplementation has been found to reduce fruit cracking by enhancing the mechanical strength of fruit tissues and promoting better water regulation within the plant (Ma and Yamaji, 2006). Furthermore, silicon's role in stimulating the plant's systemic acquired resistance (SAR) mechanism helps in reducing apple scab severity by limiting fungal growth and sporulation on the fruit surface (Fawe *et al*., 2001). Liang *et al.* (2020) demonstrated that silicon application in apple trees reduced cracking by 15% in regions with fluctuating water availability. As a result, apple orchards receiving these combined nutrient applications show lower percentages of cracked fruit compared to those without such treatments (Rosa *et al*., 2020).

Total soluble solids (TSS) (Brix^0), total sugar (%) and reducing sugar (%)

Total soluble solids (TSS) were significantly affected by different treatment combinations and cultivars (Table 2). The interaction effect was also found non-significant. The mean values for various nutrient combination showed that apple plants sprayed with 3.00 B + 18.00 Ca + 24.00 Si (gL^{-1}) resulted in maximum TSS (15.01 Brix^0) which is statistically similar with TSS (14.79 Brix^0), recorded in plants treated with nutrient combination of 2.25 B + 13.50 Ca + 18.00 Si (gL^{-1}) followed by nutrient combination 1.50 B + 9.00 Ca + 12.00 Si (gL^{-1}) and 0.75 B + 4.50 Ca + 6.00 Si (gL^{-1}) resulted in TSS of (10.23 Brix^0) and (10.22 Brix^0), respectively. Untreated plants resulted in low TSS (9.55 Brix^0). In case of cultivars, TSS was high (12.57 Brix^0) in cultivars of Royal Gala that was followed by Mondial Gala having TSS of 12.35 (Brix^0), while cultivar Treco Gala produced the minimum TSS of (12.15 Brix^0).

Table 2: *Total soluble solids (TSS) (Brix^0), total sugar (%) and reducing sugar (%) of apple cultivars as affected by foliar application of boron, calcium and silicon in combination.*

Nutrients combinations (g L^{-1})	Studied attributes		
	TSS (Brix^0)	Total sugar (%)	Reducing sugar (%)
Control (Water Spray)	9.55 d	10.17 d	7.96 e
0.75B+4.50Ca+6.0Si	10.23 c	10.54 c	8.40 d
1.50B+9.0Ca+12.0Si	12.22 b	11.52 a	9.41 b
2.25B+13.50Ca+18.0Si	14.79 a	11.50 a	9.48 a
3.0B+18.0Ca+24.0Si	15.01 a	11.27 b	9.14 c
$LSD_{0.05}$	0.63	0.08	0.08
Apple cultivars			
Royal Gala	12.57 a	11.11 a	9.01 a
Mondial Gala	12.35 ab	11.02 b	8.90 b
Treco Gala	12.15 b	10.87 c	8.731 c
$LSD_{0.05}$	0.35	0.04	0.04
Interactions	NS	NS	NS
Years			
2022	12.3	11.0	8.9
2023	12.4	11.0	8.9
$LSD_{0.05}$	NS	NS	NS
Interactions			
T x Cv	NS	NS	NS
Y x Cv	NS	NS	NS
Y x T	NS	NS	NS
Y x T x Cv	NS	NS	NS

Mean values in columns followed by similar letter (s) are statistically similar at 5% level of significance. NS = Non significant.

Data for total sugar of apple cultivars significantly affected by nutrient combination and cultivars as presented in (Table 2). The interaction effect was found non-significant. Among the nutrient combination the maximum quantity of total sugar (11.52%) was recorded in fruits sprayed with nutrient combination of 1.50 B + 9.00 Ca + 12.00 Si (gL^{-1}) that is statistically similar with the treatment of 3.00 B + 18.00 Ca + 24.00 Si (gL^{-1}), followed by 0.75 B + 4.50 Ca + 6.00 Si (gL^{-1}). The minimum total sugar (10.17%) was recorded in untreated plants. In case of cultivars, Royal Gala produced higher total sugar (11.11%), followed by Mondial Gala having (11.02%). Treco Gala produced the minimum total sugar of (10.87%).

The mean data pertaining reducing sugar (%) of apple in response to various combinations of nutrients and cultivars are presented in (Table 2). Statistical analysis of the mean data revealed that different nutrients combinations and cultivars significantly ($P \leq 0.05$) affected reducing sugar (%). Apple plants sprayed with nutrient combination of 2.25 B + 13.50 Ca + 18.00 Si (gL^{-1}) produced fruits with high reducing sugar of (9.48 %). Untreated plants resulted fruits with minimum reducing sugar content of 7.96 %. In case of cultivars Royal Gala has maximum reducing sugar content of 9.01% while Treco Gala has less reducing sugar in fruits (8.73%).

This study's findings align with previous reports, showing that the application of boron positively influenced TSS content in the studied apple cultivars. Research by Shear (1985) suggests that adequate calcium levels can improve nutrient uptake and transport, which in turn supports the metabolic processes leading to sugar accumulation in fruits. The results are related with those of Fallahi *et al*. (1997), who demonstrated that calcium sprays, when combined with other micronutrients like boron, resulted in better fruit quality and higher TSS. Similarly, Sharma *et al*. (2019) reported a significant increase in TSS levels with the combined application of Boron and Calcium in apple orchards, attributing it to enhanced carbohydrate metabolism and sugar transport. The addition of Silicon further amplified this effect by reducing oxidative stress and improving nutrient translocation. Studies by Liang *et al*. (2007) suggest that silicon application improves the plant's overall vigor, which may lead to enhanced metabolic processes, including those involved in sugar production and transport. These findings are in line with previous research by Hattori *et al*. (2005), who reported that silicon's role in stress mitigation could enhance the synthesis of secondary metabolites, including sugars. The combined application resulted in a significant increase in TSS in all the studied apple cultivars compared to the control group. This suggests that a balanced nutrient management approach involving these three elements can optimize fruit quality, particularly in terms of sweetness and flavor. Similar findings were reported by Behboudian *et al*. (1994), who observed that a balanced supply of micronutrients improves not only the physiological performance of apple trees but also the final fruit quality parameters, including TSS.

In this study, the combined application of boron with calcium and silicon significantly increased the total sugar content in the treated apple cultivars. This is consistent with earlier findings that boron promotes sugar transport and storage in developing fruit tissues (Huang *et al*., 2015). Several studies have shown that B application improves the total sugar content in apples, as it enhances the activity of enzymes involved in carbohydrate metabolism, such as sucrose synthase (Marschner, 2012). Gupta and Solanki (2017) reported that boron application in apple orchards led to an increase in sugar content by improving the translocation of carbohydrates from leaves to fruits. Similarly, Ali *et al*. (2020) demonstrated that boron enhances the activity of enzymes involved in sugar synthesis and allocation, contributing to higher total sugar levels in apple fruits. In the current study, calcium application resulted in a marked increase in total sugar levels across the tested apple cultivars. This supports the findings of Saure (2005), who proposed that calcium influences sugar accumulation by improving the transport and storage of sugars during fruit development. Research by Tian *et al*. (2019) suggested that calcium application in apples not only improves fruit firmness but also affects carbohydrate metabolism by influencing the activities of invertases and sucrose synthase, enzymes that regulate sugar breakdown and synthesis. According to research by Singh *et al*. (2020), the combined application of B, Ca, and Si significantly improved the total sugar content of apples. The synergistic effect of these nutrients not only promoted sugar accumulation but also improved overall fruit quality and storability. According to Liang *et al*. (2018), Si enhances photosynthesis and carbohydrate metabolism, leading to increased sugar content in fruits such as apples and peaches. The results of this study align with the findings of Nawaz *et al*. (2021) who reported that the co-application of boron and calcium increased sugar content in apples by improving nutrient availability and translocation. Liu *et al*. (2018) suggested that boron improves sugar metabolism by enhancing the activity of enzymes like sucrose synthase, which regulates the conversion of sucrose to reducing sugars such as glucose and fructose. This is consistent with the findings of this research, where boron treatments contributed to higher reducing sugar content in the treated apple cultivars. In this study, the application of calcium showed a noticeable improvement in the reducing sugar content of apples, supporting the hypothesis that adequate calcium supply enhances carbohydrate partitioning and overall fruit quality. This result aligns with previous findings indicating that calcium treatments improve fruit firmness and sugar concentration (Ferguson and Watkins, 1989).

The study of Ahmad *et al.* (2021) showed that the combined application of these nutrients led to a significant increase in reducing sugar content in apples, enhancing fruit sweetness and consumer acceptance.

Fruit boron content (mg kg^{-1}), leaf boron (mg kg^{-1}) and fruit calcium (mg kg^{-1})

Boron content in fruit significantly affected by foliar application of treatment combination and apple cultivars (Table 3). The apple plants sprayed with 3.00 B + 18.00 Ca + 24.00 Si (gL^{-1}) resulted in highest fruit boron content of (129.35 mg kg^{-1}) which is statistically similar with 2.25 B + 13.50 Ca + 18.00 Si (gL^{-1}), having fruit B content of (129.35 mg kg^{-1}). Whereas, lowest fruit B content (86.53 mg kg^{-1}) was recorded in untreated plants. The apple cultivars also had significant differences regarding fruit boron content. Fruit boron content was maximum (115.82 mg kg^{-1}) in Mondial Gala and was statistically similar with cultivar Royal Gala (115.69 mg kg^{-1}), while Treco Gala resulted in lowest boron content (113.88 mg kg^{-1}) in apple fruit. The interaction effect of treatment combinations (T) and apple cultivars (Cv) was also found significant (Figure 3).

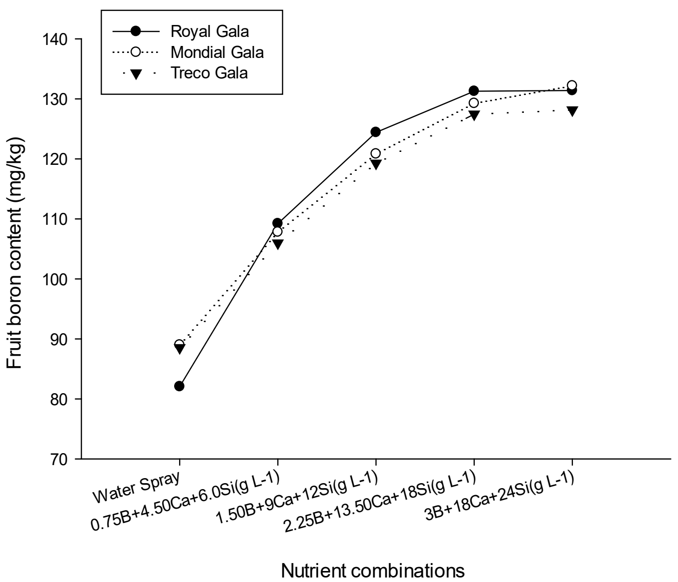

Figure 3: *Interaction between nutrients (born, calcium, silicon) and apple cultivars cultivars (Royal Gala, Mondial Gala and Treco Gala) for the fruit boron content (mg kg^{-1}) of apple cultivars.*

The data revealed that fruit Ca contents significantly influenced by the treatment combination and apple cultivars. The maximum fruit calcium content (10.00 mg kg^{-1}) was recorded in apple plants treated with 3.00 B + 18.00 Ca + 24.00 Si (gL^{-1}) in combination and statistically similar with the treatment of 2.25 B + 13.50 Ca + 18.00 Si (gL^{-1}). Similarly un-treated plants resulted in low fruit calcium content of 4.97 (mg kg^{-1}). In case of apple cultivar Royal Gala produced fruits with maximum calcium content of 8.22 (mg kg^{-1}), statistically similar with Mondial Gala (8.03 mg kg^{-1}).

Table 3: *Fruit boron content (mg kg^{-1}), leaf boron (mg kg^{-1}) and fruit calcium (mg kg^{-1}) of apple cultivars as affected by foliar application of boron, calcium and silicon in combination.*

Nutrients combinations (g L^{-1})	Studied attributes		
	Fruit boron (mg kg^{-1})	Fruit calcium (mg kg^{-1})	Silicon in fruit (%)
Control (Water Spray)	86.53 d	4.97 d	0.13 e
0.75B+4.50Ca+6.0Si	107.68 c	6.04 c	0.17 d
1.50B+9.0Ca+12.0Si	121.52 b	9.00 b	0.27 c
2.25B+13.50Ca+18.0Si	129.35 a	9.88 a	0.30 b
3.0B+18.0Ca+24.0Si	130.59 a	10.00 a	0.32 a
$LSD_{0.05}$	2.20	0.34	0.01
Apple cultivars			
Royal Gala	115.69 a	8.22 a	0.25 a
Mondial Gala	115.82 a	8.03 a	0.24 a
Treco Gala	113.88 b	7.68 b	0.22 b
$LSD_{0.05}$	1.23	0.19	0.01
Years			
2022	115.4	8.0	0.2
2023	114.9	8.0	0.2
$LSD_{0.05}$	NS	NS	NS
Interactions			
T x Cv	Figure 3	NS	Figure 4
Y x Cv	NS	NS	NS
Y x T	NS	NS	NS
Y x T x Cv	NS	NS	NS

Mean values in columns followed by similar letter (s) are statistically similar at 5% level of significance. NS= Non significant.

Statistical analysis of data exhibited that silicon content in fruit significantly affected by treatments combination and apple cultivars (Table 3). The maximum silicon in fruits (0.32%) was recorded in plants sprayed with treatment 3.00 B + 18.00 Ca + 24.00 Si (gL^{-1}) in combinations which is statistically at par with the treatment of 2.25 B + 13.50 Ca + 18.00 Si (gL^{-1}), 1.50 B + 9.00 Ca + 12.00 Si (gL^{-1})

and 0.75 B + 4.50 Ca + 6.00 Si (gL^{-1}), respectively. The apple cultivars under control treatment showed less value (0.13%) for silicon in fruits. In case of apple cultivars Royal Gall produced fruits with highest (0.25 %) silicon content and statistically similar with cultivar Mondial Gala, while cultivar Treco Gala produced fruits with lowest (0.22%) silicon content. The interaction effect of treatment combination and apple cultivars were found significant for the silicon content in fruit (Figure 4).

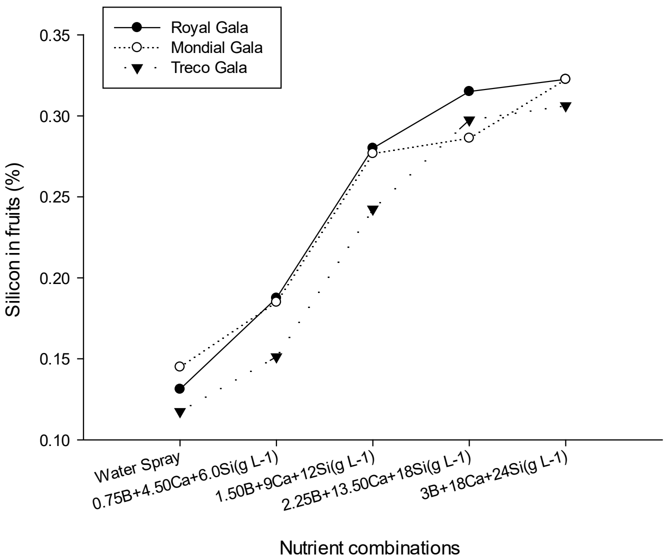

Figure 4: *Interaction between nutrients (born, calcium, silicon) and apple cultivars cultivars (Royal Gala, Mondial Gala and Treco Gala) for the fruit silicon content (%) of apple cultivars.*

Direct application of B, Ca, and Si can significantly increase its concentration in apple fruits, as observed in multiple studies. According to Marschner (2012), foliar or soil application of B has been shown to enhance B translocation to developing fruits, thus elevating the fruit's boron content. Research by Wojcik and Wojcik (2003) demonstrated that the combined application of B and Ca not only improved fruit firmness but also increased the boron and calcium content in apple fruits, suggesting a positive interaction between these two elements when balanced correctly. In apple cultivation, foliar applications of B are a common practice to correct deficiencies, as soil availability can be limited in certain regions, particularly in areas with alkaline soils (Mengel and Kirkby, 2001). Studies by Faust (1989) indicated that targeted foliar sprays during key growth stages of apples improve the distribution and uptake of boron, calcium, and silicon, leading to higher mg kg^{-1} levels in the fruit. Field studies conducted by Ahmad *et al*. (2016) on apple trees in regions with limited nutrient availability, like alkaline or boron-deficient soils, revealed that a combined application of B, Ca, and Si resulted in increased B, Ca, and Si content in fruits. In this study, Si contribution to B uptake could have enhanced boron mobility in the plant, leading to its higher accumulation in fruits. This aligns with the findings of several researchers who reported similar outcomes with the combined use of micronutrients in fruit crops (Bonomelli and Ruiz, 2010). Different apple cultivars may exhibit varying capacities for boron, calcium, and silicon uptake, and this variation could be attributed to genotypic differences in root absorption efficiency and translocation of silicon to fruits (Epstein, 1999). For example, Si accumulating cultivars tend to show more pronounced effects of Si supplementation in terms of fruit quality and stress resistance (Liang *et al*., 2015). In the context of the current study, the observed differences in fruit B, Ca, and Si content between apple cultivars could be linked to these inherent differences in boron, calcium, and silicon uptake and accumulation.

Conclusions and Recommendations

In conclusion, foliar fertilization with calcium, boron, and silicon significantly improved both yield and quality of apples, offering a cost-effective and environmentally safe approach. The combined foliar application of boron, calcium, and silicon @ 2.25 B + 13.50 Ca + 18.00 Si (gL^{-1}) demonstrated notable potential to enhance apple fruit yield and quality traits. Among the cultivars studied, Royal Gala showed superior performance in yield and fruit quality. Further research is needed to optimize the combined foliar application of boron, calcium, and silicon to achieve better yield and quality across different fruit crops and under various agro-climatic conditions. Based upon the findings of this research, the following recommendations may be suggested: Combine foliar application of boron, calcium and silicon @ 2.25B + 13.50Ca + 18.0Si (g L^{-1}) have the potential to enhance growth, yield and quality traits of apple fruits. Additionally, cultivar specific responses such as the superior performance of Royal Gala, should be studied in greater detail to identify optimal nutrient management practices tailored to different apple cultivars. Further research work is needed for the optimization of the combine foliar application of boron, calcium and silicon for better growth, yield and quality of different fruit crops under varied agro climatic conditions of Swat, Pakistan.

Novelty Statement

This research is innovative in terms of biotic and abiotic stress problems have been controlled through nutrients management without use of toxic chemicals.

Author's Contribution

Iftikhar Ahmad: Principal author, who did research experiment, analysis and write-up.
Muhammad Sajid: Major Supervisor, provided guidelines for this research experiment.

Supplementary Material

There is supplementary material associated with this article. Access the material online at: https://dx.doi.org/10.17582/journal.sja/2025/41.2.752.763

Conflict of interest
The authors have declared no conflict of interest.

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