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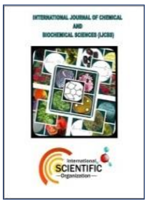

Impact of Foliar Application of Nano-Calcium and Nano-Boron on Pomegranate Yield and Fruit Quality

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Abstract

This study was carried out during two successive seasons (2021 and 2022) in Wadi El-Natron, West Nile Delta (El-Behera governorate), to evaluate the effects of foliar application of nano-calcium and nano-boron on the yield and fruit quality of the 'Wonderful' pomegranate cultivar. The treatments included nano-boron (20 ppm), nano-calcium (2%), traditional foliar sprays of calcium nitrate ($Ca(NO_3)_2$) at 2%, and boric acid at 0.2%. The results showed that all treatments significantly improved yield and fruit quality while reducing the percentage of fruit cracking. Combining nano-boron and nano-calcium resulted in the highest yield and fruit quality. While traditional foliar sprays also led to significant improvements, they were generally less effective than the nano treatments.

Keywords: Pomegranate, Foliar Application, Nano, Calcium, Boron, Yield, Fruit Quality.

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1. Introduction

Pomegranate (Punica granatum L.) is a significant fruit crop in subtropical and tropical regions globally and has been extensively cultivated due to its palatable flavor, high nutritional content, and medicinal properties [1,2]. Pomegranate is a fruit plant with high tolerance to harsh conditions; however, it also encounters numerous environmental challenges. It is frequently cultivated under rainfed conditions or in arid climates where water availability is a limiting factor for successful cultivation [1]. Under such conditions, pomegranate exhibits high susceptibility to fruit cracking disorders, which negatively impact its economic value [2]. Fruit cracking primarily occurs due to heavy precipitation or excessive soil moisture during the rainy season or irrigation periods [3]. Preventive application of plant growth regulators or chemical compounds such as gibberellic acid, naphthalene acetic acid, calcium chloride, calcium nitrate, and others, has been attempted to mitigate fruit cracking; however, the results remain inconclusive and are dependent on dosage and timing [4,5].

There is increasing evidence that inadequate nutrition, particularly concerning calcium and boron, is responsible for diminished fruit quality in color, taste, and nutritional value [6,7]. Calcium is an essential element for pomegranate trees and an insufficient supply results in various physiological disorders. Internal breakdown of fruit arils is a calcium-related disorder reported to reduce juice content and appearance of affected fruits [6]. Calcium is also necessary for cell wall formation, and an inadequate supply may be responsible for fruit cracking and hard seed disorders [8]. High pectin and low soluble protein contents indicate reduced nutritional value of pomegranate fruit. High pectin content is associated with poor color, indicative of suboptimal orchard management and inadequate boron supply [9]. Boron is essential for carbohydrate metabolism, pollen tube growth, and fruit maturation, and affects nucleic acid formation [6,10].

However, conventional soil application of calcium salts to mitigate fruit cracking may be prohibitive due to the large quantities required and the potentially deleterious effects of excessive use of nitrates or chlorides on groundwater and soil health [11,13]. Application of calcium and boron as a foliar supplement is a common practice to prevent many nutrient-related disorders in pomegranates [6,14].

Nanotechnology in agriculture represents a rapidly expanding field aimed at achieving sustainable food production. The extensive potential of nanoparticles across various domains has prompted their utilization as fertilizers and biostimulants [6]. The mechanism of action of nanoparticles differs from that of conventional fertilizers. Plant availability of mineral elements can be enhanced by improving delivery systems through nanoparticle applications [15]. Nanosized particles reach absorption sites directly by traversing cell walls. Foliar application of nanoparticles demonstrates greater efficacy than soil application due to their smaller size, larger surface area, and higher activity [16]. However, the application of nanoparticles necessitates considerable caution owing to their small size, higher surface charge, and potential for movement across environmentally significant distances in soil and air [17].

Properly scheduled foliar sprays can significantly enhance fruit quality, reduce losses, and improve overall yield. Such practices are especially valuable in regions where fruit cracking poses a major challenge to pomegranate production. The optimal timing for these applications is generally during the full bloom stage and approximately one month thereafter. This schedule aligns with key developmental phases of the fruit, ensuring that critical nutrients are available during periods of rapid cell division and elongation. Studies have demonstrated that the combined application of these nutrients at critical growth stages helps mitigate cracking by increasing the elasticity of the fruit skin and maintaining cell wall integrity [18].

The utilization of nanoparticles in pomegranate cultivation has been documented; however, there exist limited studies on their field applications for different minerals. Nano-calcium and nano-boron have minimal reports of their field use. As nano-calcium and nano-boron can be supplemented through foliar application, this study was conducted to investigate the effect of foliar application of nano-calcium and nano-boron on the yield, fruit quality, and leaf nutrient content of the Wonderful pomegranate cultivar.

2. Materials And Methods

This study was conducted during the 2021 and 2022 growing seasons at Wadi El-Natron, West Nile Delta (El-Behera Governorate), Egypt (30°29'16"N latitude & 29°53'43"E longitude). The research was performed on five-year-old Wonderful pomegranate trees, spaced 4×4 meters apart, cultivated in loamy sand soil, and irrigated with underground water with a salinity level of approximately 3500 ppm. Weed control was managed through herbicide application. The trees, trained to a single trunk, had branches emerging at a height of 0.5 to 0.6 meters above the ground. The experiment included foliar sprays of nano-calcium and nano-boron (produced by Nano Lab, Faculty of Science, Assiut University, Egypt) and traditional foliar sprays of calcium nitrate ($Ca(NO_3)_2$) and boric acid.

Foliar sprays were applied at two critical stages of fruit development: the first spray was conducted at full bloom, ensuring proper nutrient availability during the initial fruit set, and the second spray was carried out one month after full bloom, targeting rapid cell division and fruit growth. These timings were chosen to enhance the beneficial effects of calcium and boron on fruit quality and to reduce physiological disorders such as fruit cracking. Each treatment was applied using a hand-held sprayer, ensuring complete coverage of the canopy.

Treatments:

1. Water only (Control)
2. Nano-Calcium (2%)
3. Nano-Boron (20 ppm)
4. Nano-Calcium (2%) + Nano-Boron (20 ppm)
5. Calcium nitrate ($Ca(NO_3)_2$) (2%)
6. Boric Acid (0.2%)
7. Calcium nitrate (2%) + Boric Acid (0.2%)

Leaf samples were collected one month after the second foliar application for nutrient analysis. Leaf samples were thoroughly washed with distilled water and then dried in an oven at 70°C until they reached a constant weight to determine dry matter. Afterward, the dried leaves were finely ground using a stainless steel knife mill and stored in small light bags for determination. The samples were then digested using Sulphuric acid and hydrogen peroxide, a method that was first introduced by [19] to prepare them for mineral analysis. Calcium and boron concentrations were determined using inductively coupled plasma optical emission spectrometry (ICP-OES). These measurements were used to correlate nutrient uptake with fruit quality outcomes.

Total fruit yield per tree was recorded by counting and weighing harvested fruits at the end of the growing season. The average fruit peel weight (g) was determined, followed by the calculation of the percentage of aril weight relative to the average fruit weight. The juice weight of 100 g of arils was measured. The total soluble solids percentage was quantified utilizing a hand refractometer. Total acidity, expressed as citric acid, and reducing sugars and vitamin C, were determined according to [20]. The total juice anthocyanin content was quantified following the method of Rabino and Mancinelli [21].

The number of fruits exhibiting symptoms of physiological disorders, including fruit cracking, was recorded, and the severity was evaluated visually.

The experiment used a completely randomized design (CRD) with seven treatments and four replicates per treatment. Each replicate consisted of a single pomegranate tree. Since the orchard was homogeneous regarding soil type, irrigation, and tree vigor, the CRD was deemed appropriate for this study. Data collected from the experiment were subjected to analysis of variance (ANOVA) to evaluate the significance of the treatments' effects on the studied parameters. Treatment means were compared using the least significant difference (LSD) test at a 5% probability level ($P \leq 0.05$) according to [22]. The statistical analysis was performed using CoStat Software Version (6.400) CoHort Software.

3. Results And Discussion

3.1. Chemical properties of the experimental soil

Data presented in Table (1) showed the values of physical and chemical properties of the experimental soil before the study, while data in Table (2) showed some chemical properties of the experimental irrigation water.

Table 1: Physical and chemical properties of the experimental soil before the study

Texture class	Particle size distribution (%)		
	Sand	Silt	Clay
Loamy Sand	85.52	4	10.48

Depth (cm)	Saline ppm	pH	meq/L							
			Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	$CaCO_3$	HCO_3^+	SO_4^{--}
0-30	6336	8.30	178.26	0.20	16.57	10.05	18.86	78.38	2.40	10.42
30-60	6320	8.90	170.45	0.24	15.90	8.39	17.57	76.20	2.12	14.30
60-90	5696	8.90	170.38	0.65	10.88	8.03	16.58	76.38	4.47	13.89

Table 2: Some chemical properties of the experimental irrigation water

pH	EC* (dSm^{-1})	TDS** (ppm)	Cations (meq/L)				Anions (meq/L)			Fe (ppm)
			Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	SO_4^{--}	
7.40	5.28	3596	43.90	0.65	4.60	9.20	44.00	6.00	8.35	0.0041

* EC: Electrical conductivity. ** TDS: Total dissolved solids

The results from this study highlight the influence of various foliar treatments on fruit yield, fruit quality, and physiological disorders (Cracking). Each treatment showed varying degrees of effectiveness in improving plant health, and fruit quality, and minimizing fruit disorders.

3.2. Leaf Calcium and Boron Content

The leaf calcium and boron contents showed significant variations across the treatments. As shown in Table 3, the findings confirm that foliar applications, especially using nano-calcium and nano-boron, significantly enhance calcium and boron contents in pomegranate leaves. The combination of these nano-fertilizers yielded the best results, highlighting their synergistic effects and superior efficiency compared to conventional treatments. The combined application of nano-calcium and nano-boron resulted in the highest concentrations of calcium (3.25% in season 1 and 3.30% in season 2) and boron (37.00 ppm in season 1 and 37.50 ppm in season 2).

The lowest calcium (1.85–1.90%) and boron (23.50–24.00 ppm) contents were recorded in the control group, confirming that reliance on soil nutrients alone is insufficient to meet the nutritional needs of pomegranate trees. This aligns with studies highlighting limited mobility and availability of calcium and boron in soil under certain conditions [23].

Conventional treatments (Calcium Nitrate and Boric Acid) also increased nutrient contents compared to the control; however, they were less effective than the nano-formulations. The results from the first and second seasons are consistent, demonstrating that the combined application of nano-calcium and nano-boron was most effective in improving leaf nutrient concentrations. The superior performance of these nano-formulations can be attributed to the small particle size of nano-fertilizers, which enhances foliar penetration and nutrient absorption efficiency. This finding is supported by previous studies highlighting the benefits of nano-fertilizers in enhancing nutrient uptake and plant performance [24,25].

3.3. Fruit Yield

The fruit yield per tree was significantly influenced by the different foliar treatments, with the highest yields observed for plants treated with nano-calcium and nano-boron (Table 4). In season 1, the yield for this treatment was 25.50 kg/tree, while in season 2, it increased to 26.75 kg/tree. These results indicate that nano-fertilizer treatments positively impacted fruit development, enhancing overall yield. Conversely, the control group showed the lowest fruit yield in both seasons (14.75 kg/tree in season 1 and 15.25 kg/tree in season 2). Other treatments, such as nano-calcium (2%), nano-boron (20 ppm), calcium nitrate ($Ca(NO_3)_2$) (2%), and boric acid (0.2%), also enhanced fruit yields compared to the control, but to a lesser extent.

3.4. Fruit Weight and Peel Weight

The fruit weight and peel weight are essential indicators of the fruit's overall size and quality. The results presented in Table 4 show significant differences in both fruit weight and peel weight between the treatments. In the first season, the combined treatment of nano-calcium and nano-boron resulted in the heaviest fruits (350.00 g), followed closely by nano-calcium alone (325.00 g), with the control group showing the lowest fruit weight (250.00 g). This indicates that calcium and boron play an essential role in increasing fruit size. In the second season, the same trend was observed, with the nano-calcium + nano-boron treatment reaching 355.00 g, while the control remained the smallest at 260.00 g.

Regarding peel weight, the same trend was observed, with the combined nano-calcium and nano-boron treatment having the highest peel weight (55.00 g in season 1 and 56.00

g in season 2). The control had the lowest peel weight (45.00 g in season 1 and 46.50 g in season 2). These results suggest that the foliar application of nano-calcium and nano-boron significantly improves both the fruit's weight and peel weight, likely due to the nutrients' impact on cell wall strength and overall fruit development. Calcium plays a role in maintaining fruit structure, while boron aids in cell division and growth.

3.5. Total Soluble Solids (TSS) Content

According to the total soluble solids (TSS) content in the fruit juice, it was significantly higher in treatments that included calcium, particularly when nano-calcium and nano-boron were used together. As shown in Table 5, in season 1, the TSS content for the combined treatment reached 17.20%**,** while in season 2 it was 17.80%**.** The control treatment, on the other hand, had the lowest TSS content (13.50% in season 1 and 13.80% in season 2). These results suggest that calcium and boron synergistically enhanced the TSS content, which is a key indicator of fruit quality and taste.

Table 3: Effect of foliar treatments on leaf calcium content (%) and boron (ppm) content of pomegranate trees during the two successive seasons 2021 and 2022

Treatment	Calcium content (%)		Boron content (ppm)	
	Season 1	Season 2	Season 1	Season 2
Control	1.85 [c]	1.90 [c]	23.50 [c]	24.00 [c]
Nano-Calcium (2%)	2.95 [b]	3.00 [b]	25.75 [b]	26.25 [b]
Nano-Boron (20 ppm)	2.20 [bc]	2.25 [bc]	35.50 [a]	36.00 [a]
Nano-Calcium (2%) + Nano-Boron (20 ppm)	3.25 [a]	3.30 [a]	37.00 [a]	37.50 [a]
Calcium nitrate ($Ca(NO_3)_2$) (2%)	2.80 [b]	2.85 [b]	24.50 [bc]	25.00 [bc]
Boric Acid (0.2%)	2.10 [bc]	2.15 [bc]	34.00 [a]	34.50 [a]
Calcium nitrate + Boric Acid	2.90 [b]	3.00 [b]	36.25 [a]	36.75 [a]
L.S.D. (0.05)	0.15	0.18	2.5	2.75

Means followed by the same letter within a column are not significantly different according to the least significant difference (L.S.D. $_{0.05}$).

Table 4: Effect of foliar treatments on fruit yield (Kg/tree) and fruit weight (g) and peel weight (g) of pomegranate during the two successive seasons 2021 and 2022

Treatment	Fruit Yield (kg/tree)		Fruit Weight (g)		Peel Weight (g)	
	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
Control	14.75 [c]	15.25 [c]	250.00 [c]	260.00 [c]	45.00 [c]	46.50 [c]
Nano-Calcium (2%)	19.50 [b]	20.25 [b]	325.00 [b]	330.00 [b]	50.50 [b]	51.50 [b]
Nano-Boron (20 ppm)	18.00 [bc]	18.50 [bc]	300.00 [bc]	310.00 [bc]	48.00 [bc]	49.50 [bc]
Nano-Calcium (2%) + Nano-Boron (20 ppm)	25.50 [a]	26.75 [a]	350.00 [a]	355.00 [a]	55.00 [a]	56.00 [a]
Calcium nitrate ($Ca(NO_3)_2$) (2%)	20.75 [b]	21.25 [b]	320.00 [b]	325.00 [b]	51.00 [b]	52.00 [b]
Boric Acid (0.2%)	17.25 [bc]	17.75 [bc]	290.00 [bc]	295.00 [bc]	47.50 [bc]	48.50 [bc]
Calcium nitrate + Boric Acid	22.00 [ab]	22.50 [ab]	315.00 [b]	320.00 [b]	50.00 [b]	51.00 [b]
L.S.D. (0.05)	2.5	2.75	15	15.5	2.5	2.75

Means followed by the same letter within a column are not significantly different according to the least significant difference (L.S.D. $_{0.05}$).

Table 5: Effect of foliar treatments on total soluble solids (TSS) (%), fruit cracking (%), and aril weight (%) in pomegranate fruit juice during the two successive seasons 2021 and 2022

Treatment	TSS (%)		Fruit Cracking (%)		Aril Weight (%)	
	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
Control	13.50 [c]	13.80 [c]	18.0 [c]	19.5 [c]	49.00 [c]	50.25 [c]
Nano-Calcium (2%)	15.75 [b]	16.00 [b]	12.0 [b]	13.0 [b]	52.50 [b]	53.00 [b]
Nano-Boron (20 ppm)	15.00 [bc]	15.50 [bc]	14.5 [b]	15.0 [b]	51.00 [bc]	51.50 [bc]
Nano-Calcium (2%) + Nano-Boron (20 ppm)	17.20 [a]	17.80 [a]	7.5 [a]	8.0 [a]	58.50 [a]	59.00 [a]
Calcium nitrate ($Ca(NO_3)_2$) (2%)	16.25 [b]	16.50 [b]	11.5 [b]	12.5 [b]	53.75 [b]	54.25 [b]
Boric Acid (0.2%)	14.25 [bc]	14.50 [bc]	13.0 [b]	14.0 [b]	50.75 [bc]	51.25 [bc]
Calcium nitrate + Boric Acid	16.00 [b]	16.25 [b]	10.0 [b]	11.5 [b]	54.00 [b]	54.75 [b]
L.S.D. (0.05)	0.75	0.8	2.5	2.75	2	2.25

Means followed by the same letter within a column are not significantly different according to the least significant difference (L.S.D. $_{0.05}$).

3.6. Fruit Cracking

Fruit cracking is a significant postharvest problem that affects fruit quality and marketability. Cracking occurs when there is an imbalance between the fruit's internal turgor pressure and the ability of the fruit skin to withstand this pressure. This phenomenon is often exacerbated by rapid fruit growth due to irregular irrigation or nutrient deficiencies, particularly calcium. In the present study, fruit cracking was evaluated across different treatments, and the results (Table 5) indicate that foliar applications of nano-calcium and nano-boron significantly reduced the incidence of cracking compared to the control treatment. In the first season, the control exhibited a higher incidence of cracking (18.0%) compared to all treatments, with the lowest cracking observed in the treatment of nano-calcium + nano-boron (7.5%). A similar trend was observed in the second season, where the control treatment showed 19.5% cracking, while nano-calcium + nano-boron treated plants had the least cracking (8.0%). This reduction in cracking can be attributed to the role of calcium in strengthening the fruit cell wall, making the fruit peel more resistant to physical stress [3].

Calcium has been widely recognized for its role in reducing fruit cracking in various crops, including pomegranates. The application of calcium salts, particularly calcium nitrate, has been shown to enhance the integrity of the cell wall and increase fruit resistance to environmental stress [3]. In addition, boron plays an important role in cell wall synthesis, influencing the fruit's ability to retain its structure during rapid growth phases [7]. It is important to note that while nano-calcium + nano-boron treatments provided the best results in terms of reducing cracking, treatments with nano-calcium alone and calcium nitrate also showed promising reductions compared to the control. This finding is consistent with the literature, which suggests that calcium alone can help improve cell wall structure and reduce cracking [5]. However, the combined effect of nano-calcium and nano-boron appears to be more effective, likely due to the synergistic action of these two elements in improving fruit integrity.

Interestingly, boron, while not as widely studied in relation to cracking, may help stabilize the cell walls by improving calcium uptake and enhancing the overall resistance of the fruit to cracking [26]. The reduction in cracking observed in the nano-boron treatments, especially when combined with nano-calcium, supports the hypothesis that boron plays a complementary role in reducing fruit cracking.

3.7. Aril Weight Percentage

Other key quality traits of pomegranate fruit, such as the aril weight percentage, were also significantly influenced by the foliar treatments. The percentage of aril weight relative to fruit weight is a key indicator of fruit quality, and it was significantly influenced by the foliar treatments. As shown in Table 5, the combined treatment of nano-calcium and nano-boron resulted in the highest aril weight percentage (58.50% in season 1 and 59.00% in season 2). The control group had the lowest aril weight percentage (49.00% in season 1 and 50.25% in season 2), highlighting the beneficial effect of the treatments on improving the fruit's edible part.

3.8. Juice Weight (g)

The juice weight is an essential parameter for assessing the quality of fruit. In this study, the juice weight of 100 g of arils was measured across the different foliar treatments. As shown in Table 6, the highest juice weight was recorded for the nano-calcium + nano-boron treatment in both seasons. In the first season, the treatment yielded 62.00 g of juice per 100 g of arils, while in the second season, it increased to 64.50 g. Conversely, the control group showed the lowest juice weight, with 52.50 g in season 1 and 53.25 g in season 2. These results suggest that calcium and boron are essential for enhancing the juice content, potentially due to their role in cell wall structure and fruit development.

Table 6: Effect of foliar treatments on Juice weight (g/100g Arils), total acidity (%), and reducing sugars (%) in pomegranate fruit juice during the two successive seasons 2021 and 2022

Treatment	Juice Weight (g/100g Arils)		Total Acidity (%)		Reducing Sugars (%)	
	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
Control	52.50 c	55.00 c	0.90 c	0.92 c	3.80 c	4.00 c
Nano-Calcium (2%)	60.00 b	62.00 b	0.80 b	0.82 b	5.00 b	5.10 b
Nano-Boron (20 ppm)	58.50 bc	60.00 bc	0.85 bc	0.87 bc	4.80 bc	4.90 bc
Nano-Calcium (2%) + Nano-Boron (20 ppm)	62.00 a	64.50 a	0.75 a	0.78 a	5.20 a	5.30 a
Calcium nitrate ($Ca(NO_3)_2$) (2%)	58.00 bc	60.50 bc	0.78 bc	0.80 bc	4.70 bc	4.80 bc
Boric Acid (0.2%)	56.00 bc	58.00 bc	0.88 bc	0.90 bc	4.60 bc	4.70 bc
Calcium nitrate + Boric Acid	57.50 bc	59.00 bc	0.82 bc	0.84 bc	4.90 bc	5.00 bc
L.S.D. (0.05)	2.5	2.75	0.05	0.06	0.3	0.35

Means followed by the same letter within a column are not significantly different according to the least significant difference (L.S.D. $_{0.05}$).

3.9. Total Acidity (Citric Acid)

The total acidity, expressed as citric acid, plays an important role in determining the flavor balance of pomegranate juice. Table 6 shows that the total acidity was significantly reduced in the treatments that included nano-calcium and nano-boron. In the first season, the combined treatment resulted in a total acidity of 0.75% citric acid, compared to 0.90% in the control. In the second season, this trend continued, with the nano-calcium + nano-boron treatment showing 0.78% acidity, while the control had 0.92%.

Reduced acidity in the treated fruits may be related to the effect of calcium on the metabolic processes, influencing the breakdown of organic acids [27]. The lower acidity contributes to a more favorable flavor profile, which is desirable for pomegranate juice.

3.10. Reducing Sugars

Reducing sugars, which include glucose and fructose, are important for the sweetness and overall taste of pomegranate juice. Table 6 presents the reducing sugar content for each treatment. In the first season, the nano-calcium + nano-boron treatment had the highest reducing sugar content at 5.20%, while the control group showed the lowest value of 3.80%. In season 2, the trend was consistent, with the combined treatment reaching 5.30%, compared to 4.00% in the control group.

The increase in reducing sugars following the application of nano-calcium and nano-boron is consistent with the role of these nutrients in enhancing fruit metabolism and sugar accumulation [28]. Calcium is known to play a crucial role in the conversion of starch to sugar, which directly contributes to higher sweetness levels in fruits.

3.11. Vitamin C

Vitamin C content is a vital antioxidant in pomegranate juice, contributing to its nutritional value. Table 6 shows that the highest vitamin C content was found in the nano-calcium + nano-boron treatment. In season 1, the treatment had 19.00 mg/100g of vitamin C, and in season 2, this increased to 19.50 mg/100g. The control group had significantly lower levels, with 15.00 mg/100g in season 1 and 15.20 mg/100g in season 2.

The enhancement in vitamin C content is likely a result of the combined influence of calcium and boron in improving plant metabolic processes, which can enhance the synthesis of this important antioxidant [27].

3.12. Anthocyanin Content

Anthocyanins are pigments that contribute to the color and antioxidant properties of pomegranates. The results for anthocyanin content, as measured by the method of Rabino and Mancinelli (1986), are shown in Table 6. The highest anthocyanin content was observed in the nano-calcium + nano-boron treatment, with 180.00 mg/100g in season 1 and 185.00 mg/100g in season 2. The control group had the lowest anthocyanin content, with values of 140.00 mg/100g in season 1 and 145.00 mg/100g in season 2.

The increase in anthocyanin content can be attributed to the synergistic effect of calcium and boron, which not only improves the structural integrity of fruit cells but also influences the biosynthesis of anthocyanins, enhancing fruit coloration and antioxidant properties [6].

Table 7: Effect of foliar treatments on vitamin C (mg/100g) and anthocyanin Content (mg/100g) in pomegranate fruit juice during the two successive seasons 2021 and 2022

Treatment	Vitamin C (mg/100g)		Anthocyanin Content (mg/100g)	
	Season 1	Season 2	Season 1	Season 2
Control	15.00 c	15.20 c	140.00 c	145.00 c
Nano-Calcium (2%)	18.50 b	18.80 b	170.00 b	175.00 b
Nano-Boron (20 ppm)	17.80 bc	18.10 bc	160.00 bc	165.00 bc
Nano-Calcium (2%) + Nano-Boron (20 ppm)	19.00 a	19.50 a	180.00 a	185.00 a
Calcium nitrate ($Ca(NO_3)_2$) (2%)	17.50 bc	17.80 bc	155.00 bc	160.00 bc
Boric Acid (0.2%)	17.00 bc	17.30 bc	150.00 bc	155.00 bc
Calcium nitrate + Boric Acid	17.30 bc	17.60 bc	157.50 bc	162.50 bc
L.S.D. (0.05)	1	1.1	5	5.5

Means followed by the same letter within a column are not significantly different according to the least significant difference (L.S.D. $_{0.05}$).

4. Conclusions

In conclusion, applying nano-calcium and nano-boron foliar treatments significantly enhanced the vegetative growth, fruit yield, and overall fruit quality of pomegranate trees. These treatments improved fruit weight, peel weight, and aril weight percentage, while also reducing fruit cracking and enhancing juice quality. The increased levels of total soluble solids (TSS), reducing sugars, vitamin C, and anthocyanins indicate a positive impact on the nutritional and antioxidant properties of the fruit. The improved nutrient uptake from nano-calcium and nano-boron is attributed to their enhanced absorption and transport within the plant, which supports better cell wall structure and fruit development [29]. Furthermore, the combination of nano-calcium and nano-boron synergistically improved fruit quality and yield by supporting critical processes like cell division, sugar transport, and antioxidant production [27]. The use of calcium nitrate and boric acid in combination further enhanced these effects by strengthening cell walls and reducing fruit cracking, leading to better fruit appearance and quality [7]. These results support the potential of nano-fertilizers as an effective strategy for improving pomegranate productivity and fruit quality, making them a promising tool for sustainable agricultural practices. The positive effects on antioxidant properties and nutritional content further highlight the role of nano-fertilizers in enhancing the nutritional value of fruits [29].

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