



Article

Enhancing Fruit Retention and Juice Quality in ‘Kinnow’ (*Citrus reticulata*) Through the Combined Foliar Application of Potassium, Zinc, and Plant Growth Regulators

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Abstract: Improving fruit quality and reducing pre-harvest fruit drop are critical goals for *Citrus reticulata* production in Pakistan, where climatic and nutritional challenges affect yield and juice quality. This study evaluated the combined effects of plant growth regulators (salicylic acid and indole acetic acid) and nutrients (potassium and zinc) on fruit drop and juice volume in *Citrus reticulata* L. Field trials were conducted at three locations in Punjab, Pakistan (Layyah, Faisalabad, and Sargodha) using a randomized complete block design (RCBD) with five replications per treatment. Nutrients (K and Zn at 100 mg/L each) and growth regulators (SA at 100 mg/L and IAA at 5 mg/L) were applied individually or in combination at three growth stages. Statistical analyses, including PCA, ANOVA, and GGE biplot, were used to identify the most effective treatments for improving fruit juice quality and reducing fruit drop. The combined foliar application of SA + K + Zn was the most effective across all parameters, except fruit drop, juice citric acid contents, and juice pH, which were negatively affected. The highest juice potassium content was observed with K application. The PCA and GGE biplot analysis indicated that the Sargodha orchard performed best, with the SA + K treatment being the most effective there, while SA + K + Zn showed the best results at Layyah and Faisalabad for reducing fruit drop, enhancing juice volume, and improving fruit quality. However, individual fruit, juice, and juice nutrient contents traits analyses revealed that the most significant improvements in fruit and juice quality were observed at the Sargodha site instead of Layyah and Faisalabad. The treatment SA + K + Zn proved to be the most stable and consistent in enhancing citrus fruit and juice quality across all three selected locations. The findings suggest that adopting the SA + K + Zn treatment could be a practical approach for citrus farmers aiming to enhance crop yield and fruit quality, thereby supporting agricultural productivity and export potential in Pakistan.

Keywords: *Citrus reticulata*; fruit quality; pre-harvest fruit drop; plant growth regulators; foliar application



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1. Introduction

Kinnow (*Citrus reticulata* L.), a perennial evergreen cultivar of the Rutaceae family, plays a vital role in strengthening the economy of developing countries like Pakistan, where it represents 75% of the nation’s total citrus production [1]. Citrus fruits are highly sought after worldwide due to their delicious taste and flavor. In Pakistan, citrus production covers 177.22 thousand hectares, yielding approximately 2.29 million tons annually [2]. The country’s citrus production has seen a steady rise from 0.445 million tons in 1970 to 2.30 million tons in 2020, growing at an annual rate of 4.14% [3]. While ‘Kinnow’ is

cultivated across all provinces, Punjab contributes over 95% of the total crop yield, with the Sargodha region renowned for producing high-quality citrus fruits [4].

Adequate nutrient supply is critical for sustaining the long growth period required for optimal fruit development [5]. In Pakistan, however, the lack of proper nutrient management has led to issues such as poor fruit quality, smaller size, color defects, and premature fruit abscission [6]. Deficiencies in essential nutrients can hinder the production of plant growth hormones, resulting in decreased fruit size, quality, and color development [7].

The foliar application of plant growth regulators (PGRs) such as salicylic acid (SA) and indole acetic acid (IAA), along with nutrients like potassium (K) and zinc (Zn), plays a vital role in optimizing growth and improving the physio-biochemical processes in citrus crops across diverse agro-climatic regions of Pakistan [7]. Among these, potassium is essential for enhancing fruit growth, productivity, and overall development [8]. Zinc is equally crucial for improving fruit yield and quality, as its deficiency can cause cytological and morpho-anatomical changes that reduce flowering and fruit set, ultimately affecting citrus quality [9].

Auxins are commonly used in citrus to enhance juice quality and prevent excessive fruit drop [10]. Additionally, salicylic acid (SA) plays a key role in regulating physiological processes by stimulating glycine betaine production, nitrogen metabolism, photosynthesis, and antioxidant defenses, which help plants combat stress [11]. These properties protect citrus crops from various abiotic stresses, ensuring better plant health and productivity [12].

Fruit drop is a significant factor contributing to reduced citrus yields, with maximum drop occurring in the following three phases: post-blossom, June drop, and pre-harvest [13]. Harsh environmental conditions, such as drought, high temperatures, pest infestations, and strong winds, can exacerbate fruit abscission [14]. To mitigate excessive fruit drop, foliar treatments with growth regulators like auxins and gibberellins can be used, along with proper water and nutrient management for susceptible cultivars [15,16].

The novelty of this multi-location study lies in its comprehensive evaluation of the combined effects of two plant growth regulators, salicylic acid (SA) and indole acetic acid (IAA), with potassium (K) and zinc (Zn) nutrients on fruit drop control, fruit retention, yield, and juice volume in *Citrus reticulata* (Kinnow). Unlike previous studies, this research uniquely integrates plant growth regulators and nutrients across different growth stages and geographic locations, offering new insights into optimizing citrus fruit production and quality through tailored foliar treatments. The findings can potentially enhance sustainable citrus farming practices and improve yield and fruit quality in diverse agro-climatic conditions.

2. Materials and Methods

2.1. Multi-Location Experimental Sites and Soil Physio-Chemical Attributes

The current multi-locations study was conducted during the period 15 October 2019 to 25 March 2020 in three citrus orchards located in Layyah (site 1, 30.9693_ N, 70.9428_ E), Faisalabad (site 2, NIAB Orchard, 31.4504_ N, 73.1350_ E), and Sargodha (site 3, 32.0740_ N, 72.6861_ E). The experiment was laid out using a randomized complete block design (RCBD) with factorial arrangements and five replications per treatment. At each experimental site, 63 citrus plants (7 in each row) were selected. For the estimation of the physio-biochemical parameters, soil samples were randomly cored from each selected orchard up to 30 cm in depth following a “W” scheme with the help of an instrument called an auger. Soil attributes such as soil texture, pH, and electrical conductivity were estimated using pH (HI-8520, Hanna, Germany) and EC meters (WTW, Germany), respectively. While soil P contents were analyzed using the method of Olsen [17], K⁺ contents were estimated by following the protocol established by Simard [18], Na contents by a flame photometer (Jenway PFP 7, UK), and Zn concentration was assessed by following the protocol of Soltanpour and Schwab [19]. Other soil parameters, such as soil saturation percentage, carbonates, bicarbonates, and the sodium adsorption ratio were measured using the method of Estefen et al. [20], as shown in (Table 1).

Table 1. Physio-chemical characteristics of soils (0–60 cm) and irrigation water of three citrus orchards.

Parameters	Layyah	Faisalabad	Sargodha
Soil texture	Sandy-loam	Clay-loam	Clay-loam
Soil saturation (%)	26.25	37.50	37.00
ECe (dS m ⁻¹)	1.74	0.93	1.85
pH	8.42	7.84	7.94
Sodium adsorption ratio (mmol ½ L ⁻¹ /2)	1.98	0.96	2.02
Organic matter (%)	0.15	0.18	0.25
NO ₃ –N (mg kg ⁻¹)	19.00	18.90	17.50
Available phosphorus (mg kg ⁻¹)	6.15	7.25	10.48
Sodium (mg kg ⁻¹)	94.50	72.00	141.00
Calcium + Magnesium (meq kg ⁻¹)	4.82	5.07	5.25
Zinc (mg kg ⁻¹)	0.33	0.68	0.50
Potassium (mg kg ⁻¹)	8.60	16.85	20.15
Carbonates (meq kg ⁻¹)	Nil	Nil	Nil
Bicarbonates (meq kg ⁻¹)	5.40	4.70	6.00
Irrigation water analysis			
EC (dS m ⁻¹)	1.58	1.02	1.40
pH	8.20	8.15	8.20
Residual sodium carbonate	1.20	1.50	1.70
Sodium (mg L ⁻¹)	78.0	54.0	75.0
Chloride (meq L ⁻¹)	2.20	2.00	1.90
Potassium (mg L ⁻¹)	9.00	7.00	10.0
Calcium + Magnesium (meq kg ⁻¹)	4.20	3.00	3.50
Carbonates (meq kg ⁻¹)	Nil	Nil	Nil
Bicarbonates (meq kg ⁻¹)	5.40	4.50	5.20
SAR (meq L ⁻¹)	2.34	1.92	2.47

Values represent the mean of the soil and irrigation water data taken during 2019.

Each selected citrus orchard was irrigated with tube-well water, and its physio-biochemical characteristics were estimated. Electrical conductivity and pH were determined with EC and pH meters. Meanwhile, K and Na contents were measured by flame photometer. Additionally, carbonate, bicarbonate, chloride, calcium + magnesium, residual sodium carbonate, and the sodium absorption ratio were estimated according to Estefen et al. [20], as reported in Table 1.

2.2. Treatments

In the current work, foliar treatments of Zn, K, SA, and IAA were applied alone or in combination. In each selected orchard, NPK fertilizers were applied after the harvest of the previous year's fruits (March 2019) with an appropriate ratio N:P₂O₅:K₂O (100:50:75 kg ha⁻¹) as urea (N 46%), diammonium phosphate (DAP; P₂O₅ 46%), and sulfate of potash (SOP; 50% K₂O). The selected citrus plants were foliar-sprayed with 100 mg L⁻¹ SA, 5 mg L⁻¹ IAA, 100 mg L⁻¹ K, and 100 mg L⁻¹ Zn, and their combinations were K + SA, Zn + SA, IAA + SA, and K + Zn + SA, whereas control plants were treated with normal distilled water. These foliar treatments were applied thrice at the flower initiation (first spray), fruit formation (second spray), and fruit-color initiation stages (third spray). All three selected orchards contained citrus trees that were 10 to 15 years old. Each orchard has 11 rows, with 11 trees per row (totaling 121 trees). Out of the 11 plants in each row, the two peripheral (edge) plants were excluded and considered non-experimental. The remaining nine plants (in each row) were randomly sprayed with a specific treatment and five replications per treatment were maintained. The spray was applied only to the foliar parts of the tree, ensuring that all leaves, flowers, and fruits were wetted with the treatment solution at each specific stage.

2.3. Growth and Yield Data Collection

Twenty fruit samples per plant were randomly collected from both treated and non-treated plants, and the fruit diameter, height, and width were assessed with the help of measuring tape and peel thickness by digital vernier caliper. The fruit shape index was estimated by using the protocol of Brewer et al. [21], fruit weight via weighing balance (JC-1202A, A&D, Company, USA), and fruit juice volume was evaluated by a graduated cylinder. Fruit dropping was computed by the formula given by Shani et al. [22] in the first week of September.

2.4. Juice Quality and Chemical Analysis

Juice volume was determined after mechanical extraction from fruits of equal size selected from all sites. Juice pH was determined by pH meter, juice EC was measured using an EC-meter (LF538, WTW, Germany), and total solids in the juice were determined by refractometer. Citric acid was estimated by titrating the juice against 0.1 N sodium hydroxide, and ascorbic acid by reducing 2,6-dichlorophenol indophenol with the juice. N, P, K, Ca, and Na contents in juice were also analyzed as described elsewhere [23].

2.5. Statistical Analysis

The data collected from the experiments were analyzed using the Statistix-10 software. A two-way analysis of variance (ANOVA) was conducted to assess the effects of different treatments on various traits. The least significant difference (LSD) test was used to compare treatment means at a 5% probability level. ANOVA helped (Table 2) determine the significance of each treatment across the selected sites. Additionally, principal component analysis (PCA) and GGE (genotype and genotype by environment interaction) biplot analysis were performed using “R software” (version 4.4.2). PCA helped reveal variations in the observed attributes, while the GGE biplot identified the most promising treatment for each location. Furthermore, the multi-trait genotype-ideotype distance index (MGIDI) was employed to select the most consistent and effective treatment across multilocation trials.

Table 2. Means of the sum of squares for all the investigated fruit and juice quality parameters in citrus orchards treated with Zn, K, and PGRs alone or in combination.

CO	DF	FSI	PT	FD	FW	JV	pH	EC	TSS	CA	AA	TSS/Acid	N	P	K
S	2	0.27 ***	71.67 ***	2 ***	29,578 ***	897 ***	0.026 ns	1.6 ***	29.9 ***	0.1 ***	1943.6 ***	329.6 ***	0.04 ***	0.07 ***	1.2 ***
T	8	0.01 ***	2.4 ***	451 **	9644 ***	801 ***	0.028 ns	0.2 ***	5.8 ***	0.1 ***	37.1 ***	38.7 ***	0.21 ***	0.77 ***	2.7 ***
S × T	16	0.002 ***	0.41 ***	19 ***	1145 ***	42.5 ***	0.024 ns	0.1 ***	0.9 ***	0.003 ***	6.9 ***	1.8 ***	0.01 ***	0.01 ***	0.08 ***
Error Total	108 134	0.001	0.02	0.2	119.3	3.7	0.03	0.02	0.01	0.0002	0.2	0.06	0.001	0.001	0.005

* Showing significant differences among all the applied drought stress treatments $p > 0.001$ ***, $p < 0.01$ **, $(0.01 < p > 0.05)$ *, $p > 0.05$, ^{ns} (non-significant); CO, citrus orchard; DF, degree of freedom; FSI, fruit shape index; PT, peel thickness; FD, fruit dropping; FW, fruit weight; JV, juice volume; pH, juice pH; EC, juice EC; TSS, total soluble sugars in juice; CA, juice citric acid content; AA, juice ascorbic acid concentration; TSS/Acid, TSS/Acid ratio of fruit juice; N, fruit juice nitrogen concentration; P, fruit juice phosphorus contents; and K, fruit juice potassium content.

3. Results

3.1. Kinnow Fruit Quantity and Quality Analyses

The current experiment systematically demonstrated that the foliar application of nutrients (potassium “K” and zinc “Zn”) combined with plant growth regulators (PGRs) significantly enhanced various fruit quality traits in *Citrus reticulata*. These improvements were consistent across all experimental sites (Sargodha, Faisalabad, and Layyah), although notable differences were observed between treatments and locations.

According to the fruit shape index [the ratio of the longitudinal diameter to the transverse diameter], foliar applications of PGRs and nutrients significantly ($p \leq 0.05$) improved the fruit shape index. The highest fruit shape index was recorded in fruits from

plants treated with a combination of salicylic acid (SA) and potassium (K), followed by the SA + K + Zn, SA + IAA, SA, and K treatments. In contrast, the control group exhibited the lowest fruit shape index, followed by plants treated with SA + Zn, IAA, and Zn alone (Figure 1A). Among the locations, fruits from Sargodha displayed the best shape index, followed by those from Faisalabad and Layyah.

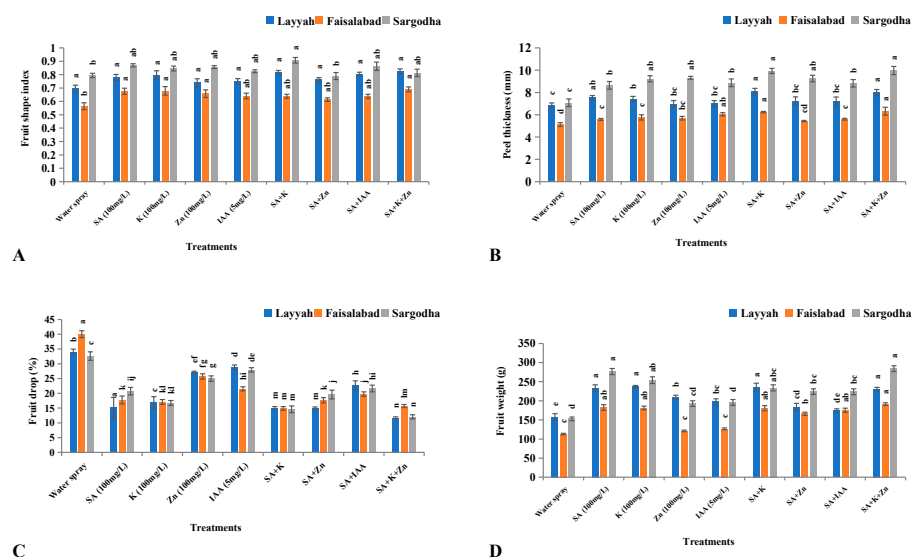


Figure 1. Effect of foliar application of plant growth regulators (PGRs) and nutrients on fruit shape index (A); peel thickness (B); fruit drop percent (C); and fruit weight (D); in citrus orchards at different selected locations. [Bars sharing similar alphabets did not differ significantly].

Peel Thickness: Peel thickness was significantly ($p \leq 0.05$) increased by the foliar application of PGRs and nutrients, with the control group having the thinnest peels (Figure 1B). Among the treated plants, the thickest peel was observed in fruits from trees sprayed with SA + K + Zn. Fruits from the Sargodha orchard had the thickest peels, followed by Layyah, while fruits from Faisalabad showed the thinnest peels.

Fruit Drop Rate: The highest fruit drop rates were observed in control plants across all sites, while the lowest rates were recorded in plants treated with SA + K + Zn. Conversely, the control group had the highest fruit drop rate (Figure 1C). Among the orchards, the Sargodha citrus orchard exhibited the lowest fruit drop, followed by Layyah and Faisalabad.

Fruit Weight: Fruit weight was significantly ($p \leq 0.05$) affected by foliar applications of PGRs and nutrients (Table 2). The heaviest fruits were produced by plants treated with SA + K + Zn, which were statistically similar to those from plants treated with K, SA, and SA + K. Among the locations, the Sargodha orchard produced the heaviest fruits, followed by Layyah and Faisalabad (Figure 1D). This experiment highlighted the effectiveness of foliar nutrient supplementation and plant growth regulators in improving key fruit quality parameters, with variations across sites influencing the outcomes.

3.2. Juice Quality Analyses

The foliar application of PGRs or nutrients significantly influenced fruit juice quality parameters except for juice pH (Table 2). However, a slight increase in fruit juice pH was observed in plants treated with SA + K + Zn and SA + K compared to other treatments. Variations in juice pH across the different sites were also non-significant, though juice from the fruit of the Layyah orchard exhibited marginally higher pH levels, followed by Faisalabad and Sargodha (Figure 2A). In contrast, the foliar application of PGRs and nutrients significantly ($p < 0.05$) impacted juice electrical conductivity (EC) (Table 2). The highest EC levels were recorded in fruits from trees treated with SA + K, which were statistically comparable to those treated with SA + K + Zn. The lowest EC was found in the juice from untreated control trees (Figure 2B). Variations in EC were also site-dependent,

with the highest values recorded at the Layyah orchard, followed by Sargodha, and the lowest EC in juice recorded at the Faisalabad orchard (Figure 2B).

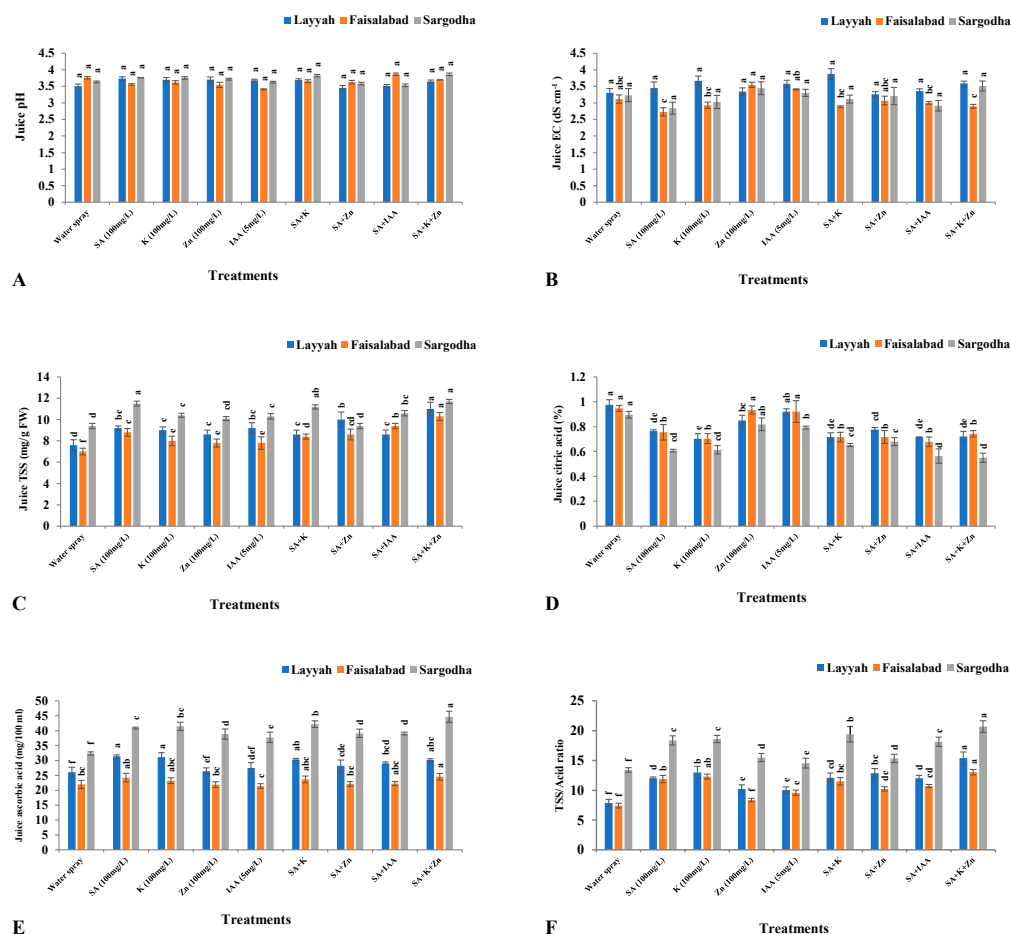


Figure 2. Effect of foliar application of plant growth regulators (PGRs) and nutrients on fruit juice pH (A); electrical conductivity (EC) (B); total soluble solids (TSS) (C); citric acid percentage (D); ascorbic acid concentration (E); and juice TSS/acid ratio (F) in fruit juice of citrus orchards in selected locations. [Bars sharing similar alphabets did not differ significantly].

Total Soluble Solids (TSS): TSS content in the fruit juice was significantly influenced by the foliar application of PGRs and nutrients like K and Zn across all orchards (Table 2). The highest TSS values were observed in juice from trees treated with SA + K + Zn, while untreated trees had the lowest TSS values. Significant site-wise differences in TSS were also noted, with the Sargodha orchard producing juice with the highest TSS content, and the Faisalabad orchard producing juice with the lowest TSS content (Figure 2C).

Citric Acid Content: Foliar applications also affected citric acid levels in the juice. The highest citric acid content was found in juice from untreated trees, whereas the lowest levels were recorded in juice from trees treated with SA + IAA, which was statistically similar to SA + K + Zn and K-treated trees (Figure 2D). Among the orchards, the Sargodha orchard had the lowest citric acid content, followed by Layyah and Faisalabad.

Ascorbic Acid Content: The ascorbic acid concentration in fruit juice was significantly enhanced by the foliar application of PGRs and nutrients (Table 2, Figure 3A). The highest ascorbic acid content was found in juice from trees treated with SA + K + Zn, which was statistically comparable to juice from trees treated with SA, SA + K, and K alone. The control group (untreated trees) had the lowest ascorbic acid levels. Site-wise, ascorbic acid content varied, with the highest levels found in juice from the Sargodha orchard, followed by Layyah and Faisalabad (Figure 3A).

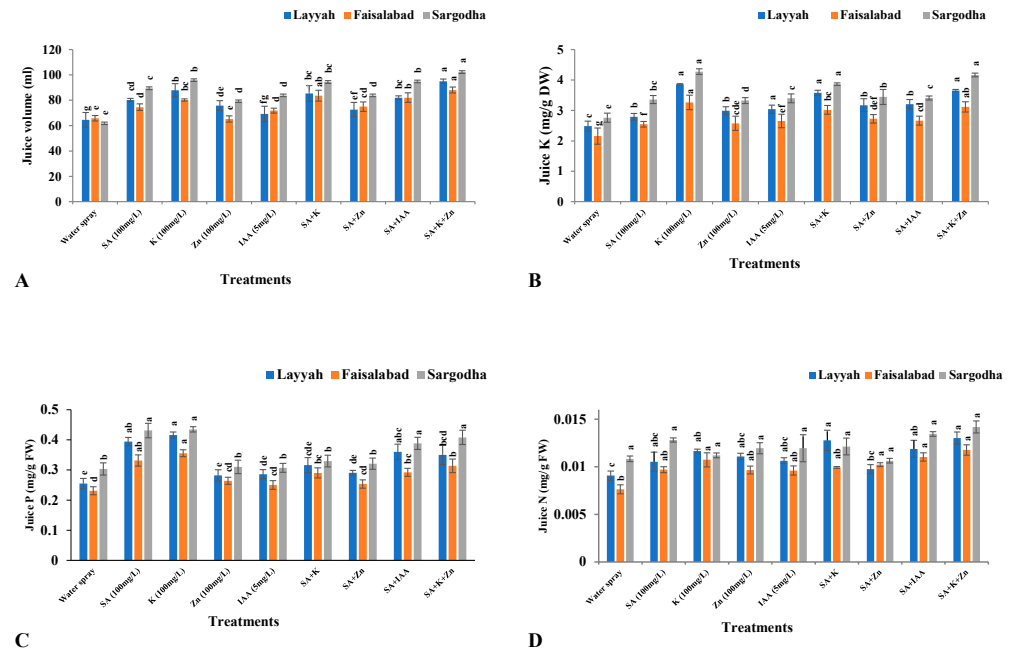


Figure 3. Effect of foliar application of plant growth regulators (PGRs) and nutrients on fruit juice volume concentration (A); fruit juice potassium contents (B); fruit juice phosphorus content (C); and fruit juice nitrogen contents (D) in citrus orchards of selected locations. [Bars sharing similar alphabets did not differ significantly].

TSS/Acid Ratio: The TSS/acid ratio, a crucial quality indicator, was significantly influenced by foliar applications of PGRs and nutrients (Table 2). The highest TSS/acid ratio was observed in juice from plants treated with SA + K + Zn, while the lowest ratio was found in juice from untreated plants (Figure 3D). Among the locations, the Sargodha orchard yielded the highest TSS/acid ratio, while the Faisalabad orchard had the lowest (Figure 3D).

Fruit juice volume: A significant increase in fruit juice volume was observed after the foliar application of PGRs and nutrients (Table 2). The highest juice volume was recorded in fruits from plants treated with SA + K + Zn, while the lowest volume was found in fruits from untreated control plants. There were also significant site-to-site variations ($p < 0.05$) in fruit juice volume, fruits with the Sargodha orchard producing the highest juice volume, followed by Layyah and Faisalabad (Figure 3A).

3.3. Fruit Juice Nutrient Contents

The foliar application of PGRs or nutrients significantly ($p \leq 0.05$) affected nitrogen (N), phosphorus (P), and potassium (K) contents, specifically. The highest fruit juice potassium (K) contents were observed in fruits from trees sprayed with K alone, closely followed by those treated with SA + K + Zn and SA + K (Figure 3B). In contrast, the lowest K content was found in juice from untreated trees. Site-to-site variations were also significant, with fruits from the Sargodha orchard having the highest juice K content, while those from the Faisalabad orchard had the lowest juice K content (Figure 3B).

Fruit juice phosphorus (P) contents in fruit juice were similarly enhanced by foliar applications of PGRs and nutrients (Table 2, Figure 3C). The highest fruit juice P contents were found in juice from fruits of trees sprayed with K alone, with statistically similar values observed for trees treated with SA. The lowest P contents were recorded in juice from untreated trees (Figure 3C). Site-specific differences were also significant, with the highest P contents found in fruit juice from the Sargodha orchard, followed by Layyah and Faisalabad orchards (Figure 4B).

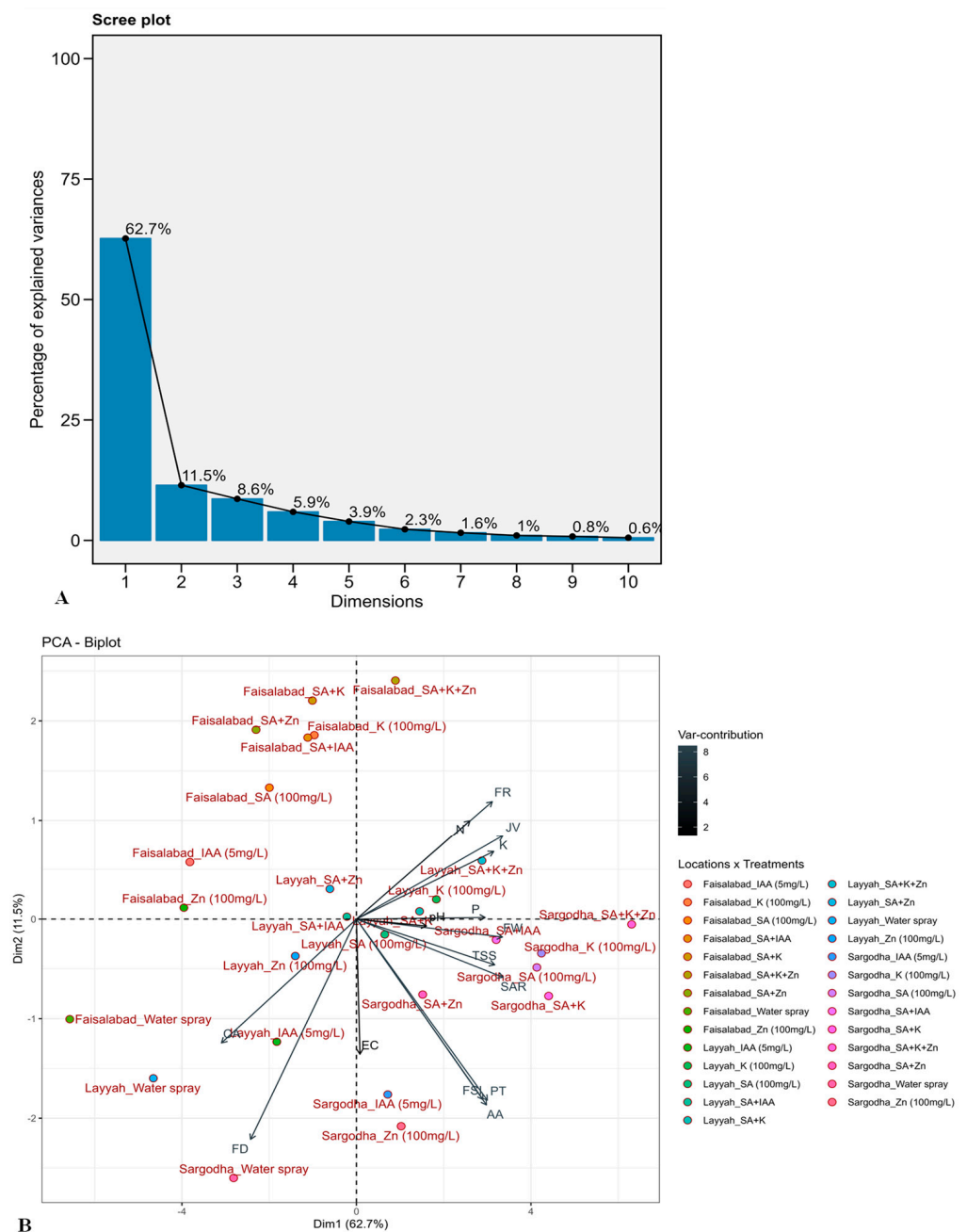


Figure 4. (A) Scree plot representing the contribution of principal components towards cumulative variability and (B) depicting the principal component analysis of studied traits under varying treatments alone or in combination.

Nitrogen (N) contents in fruit juice also increased significantly following the foliar application of PGRs and nutrients. The maximum N contents were recorded in fruit juice from trees treated with SA + K + Zn, followed by SA + IAA and SA + K. The lowest N contents were found in juice from untreated trees, closely followed by those treated with SA + Zn and SA alone (Figure 3D). Similarly to other parameters, juice N content varied across locations, with the highest levels found in juice from fruits of the Sargodha orchard, followed by Layyah and Faisalabad.

3.4. Principal Component Analysis

To better understand the variation in fruit quality traits resulting from the different individual and combined treatments, a Principal Component Analysis (PCA) was conducted. The analysis focused on the first two principal components (PCs) due to their higher contribution to the total cumulative variability. Specifically, PC-1 accounted for 62.7% of the total variability, while PC-2 contributed an additional 11.5%. These two components together captured a substantial portion of the data's variation, making them key in interpreting the results (Figure 4A).

PC-1 was primarily associated with several important fruit quality traits, including nitrogen content (N), juice volume (JV), total soluble solids (TSS), fruit weight (FW), peel thickness (PT), and fruit shape index (FSI). A strong, synergistic positive interaction was observed among these traits, indicating that improvements in one were generally accompanied by improvements in others. For instance, treatments that increased fruit weight often also enhanced juice volume, nitrogen content, and fruit shape index, suggesting a coherent pattern of positive relationships among these key parameters (Figure 4B). On the other hand, PC-2 was mainly characterized by traits such as citric acid (CA) and fruit drop (FD). Interestingly, these traits exhibited antagonistic relationships with the fruit quality traits in PC-1. This suggests that while certain treatments enhanced juice volume and other positive attributes, they might simultaneously reduce citric acid content and fruit drop (Figure 4B).

Regarding the site-specific effects, the combined foliar supplementation of salicylic acid (SA), potassium (K), and zinc (Zn) at the Layyah site demonstrated a highly favorable interaction in boosting pivotal traits such as nitrogen content (N), juice volume (JV), and potassium content (K) in the juice. This highlights Layyah as a site where the combination of SA + K + Zn was particularly effective in improving the quality of the fruits (Figure 4B). At the Sargodha site, a different set of trends emerged. The foliar application of SA + Indole acetic acid (IAA) significantly enhanced fruit weight (FW), underscoring the effectiveness of this treatment in promoting heavier fruits. Additionally, the application of SA alone resulted in a marked improvement in the total soluble solids (TSS) content of the fruit juice, emphasizing the role of SA in enhancing the sweetness and overall quality of the fruit produced at this site (Figure 4B).

These findings underscore the importance of both the specific combination of treatments and orchard location in influencing fruit quality traits. The PCA provided a clear separation of these relationships, helping clarify how certain traits were positively or negatively influenced by the treatments in different contexts (Figure 4).

3.5. GGE Biplot Analysis

The GGE biplot analysis, introduced by Yan and Wu [24], was employed to evaluate the effects of different treatments on citrus fruit cultivation across multiple sites, including Sargodha, Layyah, and Faisalabad. This analysis helps to clearly understand how effectively each treatment improves physiological traits and fruit quality. Moreover, GGE biplot analysis is useful for identifying the most suitable site for citrus cultivation. The average environmental coordinate (AEC) system was also used to assess the overall performance of each treatment applied. In the GGE biplot, the first principal component (PC-1), which accounts for 72.27% of the total variance, represents fruit quality, while the second principal component (PC-2), contributing 19.3% of the variance, reflects the stability of each treatment across the different citrus orchards. The results indicated that the foliar application of SA + K was most effective in enhancing fruit quality at the Sargodha site. In contrast, at the Faisalabad and Layyah sites, the combination of SA + K + Zn significantly improved fruit quality and juice concentration (Figure 5A).

The mean vs. stability analysis of the GGE biplot revealed that treatments positioned closest to the mean line contributed the most to improving citrus fruit quality. The exogenous application of SA + K at Sargodha played a crucial role in enhancing fruit attributes, as it was located near the arrow on the line. Conversely, the lowest impact on fruit quality was observed in plants sprayed with water across all sites (Figure 5B). The dotted line on

the biplot represents the mean line, illustrating the stability of each treatment across the different citrus orchards. The analysis further revealed that the SA + K + Zn treatment was the most effective in improving fruit quality traits at the Faisalabad and Layyah orchards. However, at the Sargodha orchard, the SA + K treatment yielded the most desirable fruit quality outcomes. In contrast, water spray had a minimal impact on improving fruit quality parameters at any of the selected sites (Figure 5B). Additionally, foliar supplementation with SA + K proved to be the most effective in enhancing citrus fruit quality, followed closely by IAA application. However, treatments with SA + Zn, SA alone, Zn, and IAA individually did not produce the desired improvements in fruit quality and juice volume.

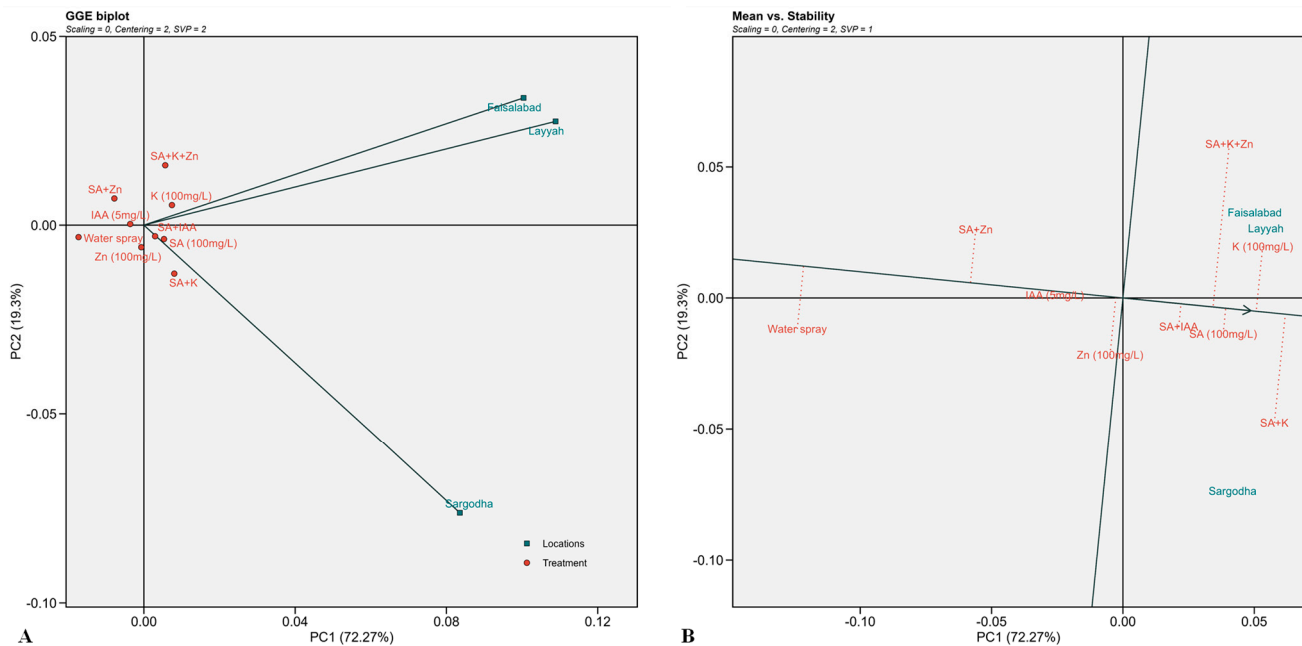


Figure 5. (A) GGE plot among two principal components (PC-1 and PC-2) demonstrating the stability of each treatment in selected sites. (B) “Mean vs. Stability” representing GGE biplot unveiling the effectiveness of each treatment at multiple locations.

3.6. GGE Biplot (Which-Won-Where)

The GGE biplot (which-won-where, constructed using R software, identifies the best-performing treatments at specific sites. The polygon representation helps differentiate crossover from non-crossover treatments [25]. This analysis is useful for selecting suitable environmental locations for ‘Kinnow’ cultivation, as well as for identifying PGRs or nutrients that can improve citrus fruit and juice quality and yield in Pakistan. Treatments within the same sector indicate the best choices for each orchard. Each sector of the biplot contains one “winning” treatment at the vertex of the polygon, signifying the treatment most favorable for enhancing citrus fruit quality at the respective location [26]. The biplot shows that the SA + K + Zn and K treatments are in a common sector and are suitable for improving citrus fruit quality in Faisalabad and Layyah. However, the SA + K treatment emerged as the winning treatment for the Sargodha site, proving essential in regulating fruit quality parameters (Figure 6). In contrast, the treatments IAA and Zn did not associate with any sector across the locations. Their effects were minimal and fell below the grand mean of other treatments. However, the proximity of the IAA treatment to the origin of the biplot suggests it has general stability across sites. This scenario illustrates the interaction between treatments and locations, as each site has a specific winning treatment. Positive interactions occurred between treatments and locations within the same sector, while opposite sectors revealed antagonistic interactions [27].

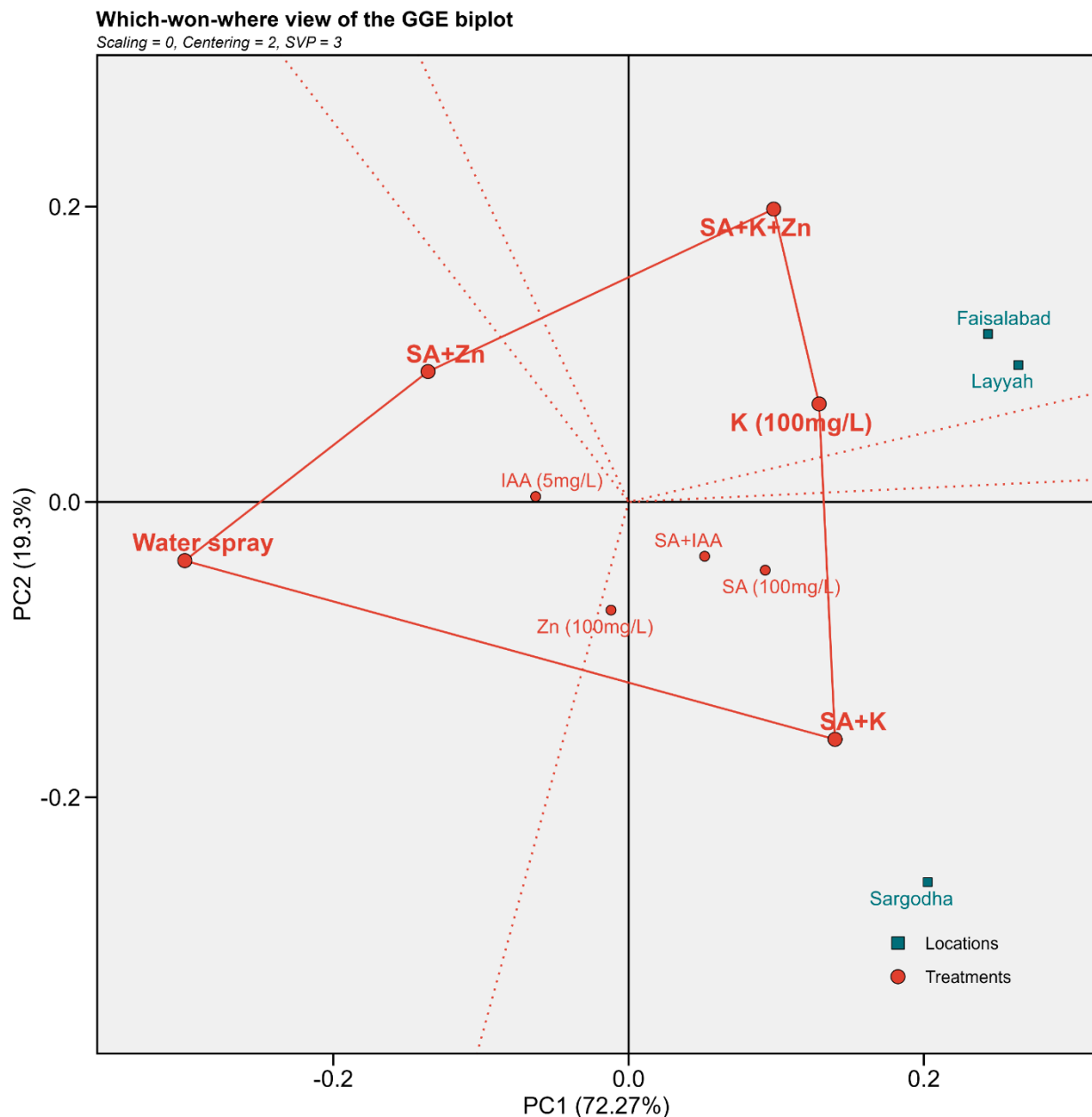


Figure 6. GGE biplot which-won-where representing the interaction between treatments and locations, unraveling the most promising treatment for the particular selected site.

3.7. Multi-Trait Genotype-Ideotype Index (MGIDI)

The MGIDI analysis was conducted separately for each location to determine the most suitable treatment for each selected site. Identifying effective treatments to achieve desired traits in citrus fruits can help farmers maximize citrus yields per hectare. According to this novel index, two treatments, SA + K and SA + K + Zn, were particularly effective in enhancing citrus fruit quality and juice quantity at the Sargodha site (Figure 7A–C). Additionally, Figure 7B indicates that fruit drop is the most consistent factor contributing to the decline in citrus productivity.

However, the Faisalabad site presented a slight variation, where SA + K + Zn and SA + IAA were the key treatments for achieving the desired outcomes. In contrast, at the Layyah site, SA + K and potassium (K) alone were crucial in attaining the desired traits in citrus fruits. Overall, our findings suggest that the Sargodha site is highly conducive to citrus cultivation due to its favorable traits, including lower fruit drop and citric acid levels

compared to the other two locations. Notably, the SA + K + Zn treatment significantly reduced fruit drop at the Sargodha site compared to other treatments.

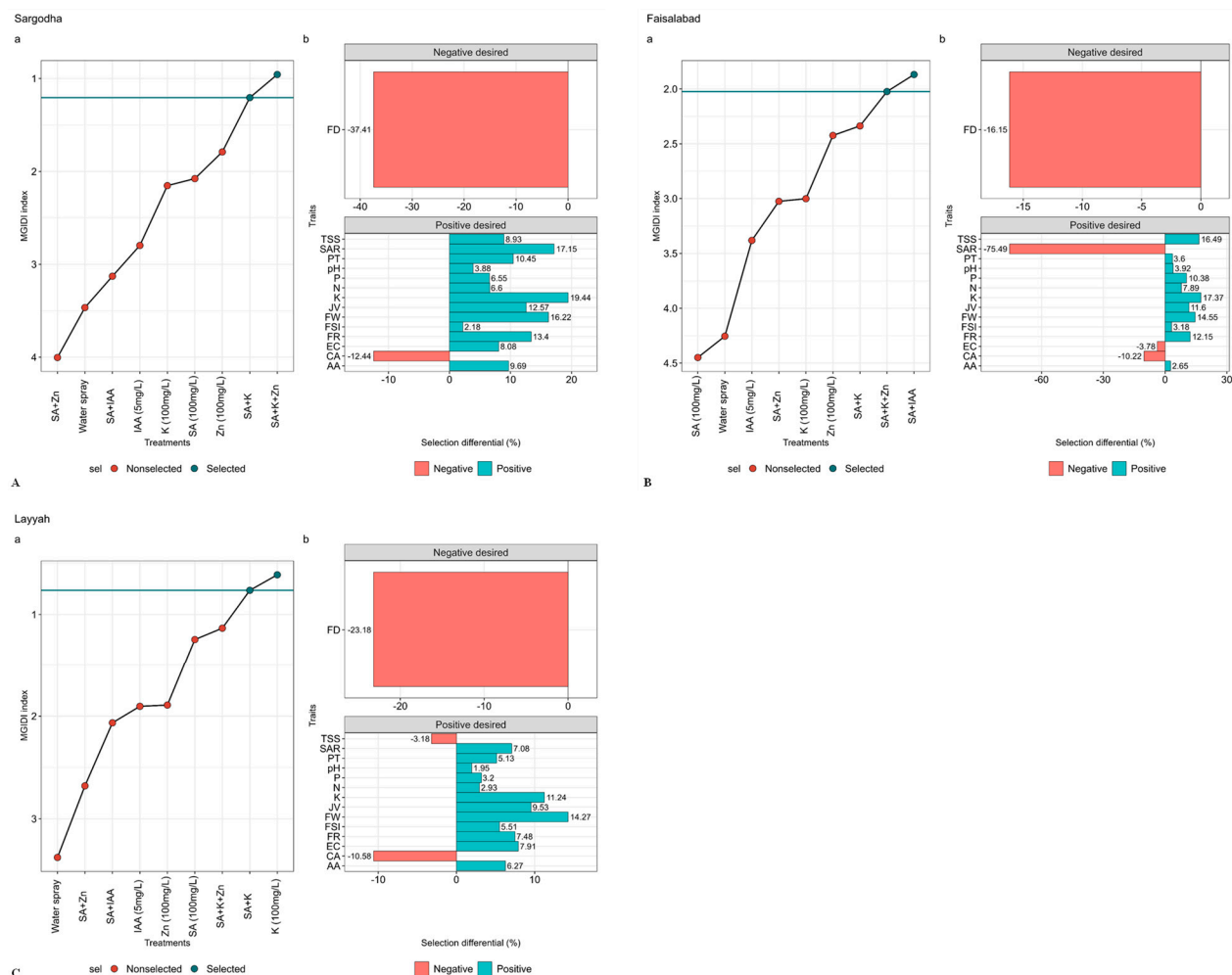


Figure 7. Multi-trait genotype ideotype index (MGIDI) for each selected location revealed promising treatments for particular sites. (A–C) (a) shows different treatments applied on the x-axis, and the y-axis indicates the MGIDI index values. Treatments below the horizontal threshold line are considered selected treatments highlighted with green color, while those above are non-selected treatments indicated with red color. Selected treatments are closer to the ideotype, revealing better performance based on the desired traits. (A–C) (b) demonstrates the selection differential for each trait. The top panel depicted the negative desired selection of FD, while the below panel demonstrated the positive and negative bars among the traits analyzed at three studied locations.

4. Discussion

The foliar application of potassium (K) and zinc (Zn) has been shown to significantly increase fruit yield by enhancing fruit weight and size in citrus plants [28]. The observed increases in fruit weight and shape index (size) with plant growth regulators (PGRs) and nutrient treatments (Figures 1A and 2A) can be attributed to the stimulation of plant growth and fruit development processes. These findings are consistent with those of Trejo et al. [29], who demonstrated that combinations of PGRs can substantially affect fruit weight and size. Regarding fruit retention (Figure 1C), the current results confirm the findings of Vani et al. [30], who reported that foliar applications of growth regulators and nutrients significantly improve fruit retention by reducing pre-harvest fruit drop (Figure 1C,D). In this study, trees treated with SA + K + Zn exhibited the minimum fruit drop, while those in control conditions had the maximum fruit drop across all orchards (Figure 1C). However,

fruit drop varied by location, with the lowest levels recorded in Sargodha compared to Layyah and Faisalabad. The combination of K, Zn, IAA, and other treatments proved effective in reducing fruit drop until final harvest, ultimately boosting fruit yield. Similar results were reported by Ferrara et al. [31], who found that the foliar applications of SA, 2,4-D, K, and Zn increased fruit retention and decreased fruit drop in citrus. Additionally, the foliar supplementation of SA + K + Zn can significantly improve fruit retention per tree by reducing fruit drop [32]. Citrus fruit drop was a major issue across all orchards, primarily caused by factors such as limited water availability during flowering/fruiting, temperature fluctuations, and nutrient deficiencies, leading to hormonal imbalances [33]. Citrus is highly nutrient-sensitive, and any imbalance can negatively impact fruit quality [34], as seen in the control plants (Figure 1D). Thus, the proper care of plant health is crucial to support fruit development and reduce fruit drop, ultimately increasing yield.

The application of Zn, K, and PGRs significantly enhanced fruit weight across all orchards (Figure 2A), with the highest fruit weight observed in plants treated with SA + K + Zn. A previous report conducted by Ashraf et al. [35] also attributed increases in fruit weight to the combined use of SA, K, and Zn, while Shah et al. [36] confirmed the role of PGRs and nutrient management in this regard. These findings suggest that such treatments are essential for improving both fruit yield and quality. Peel thickness was not significantly affected by the treatments (Figure 1B), although fruits from SA + K + Zn-treated plants had thicker peels across all orchards, enhancing shelf life as thicker peels help fruits stay fresh longer. Consumers prefer such fruits for their extended freshness. Similarly, the non-significant influence of PGRs and nutrients on peel thickness was reported by Anwar et al. [6], although Yao et al. [37] noted that Zn application can increase peel thickness.

The foliar application of PGRs (SA and IAA) and nutrients (K and Zn) significantly increased juice volume across all orchards (Figure 2B). The combination of SA + K + Zn was particularly effective in enhancing juice content, as confirmed by Majeed et al. [38], who reported similar findings with Zn and K application, and Jain et al. [39] observed substantial juice volume increases with PGRs and nutrient treatments. This improvement is crucial for citrus growers, as juice factories prioritize fruits with a higher juice content, leading to better economic returns. The juice pH was only slightly affected by the treatments, with fruit from SA + K + Zn-treated plants showing a marginally higher pH (Figure 2C). However, the electrical conductivity (EC) of the juice increased significantly following the foliar application of PGRs and nutrients at all orchards (Figure 2D). Similarly, juice total soluble solids (TSS) increased across all orchards, with the highest TSS observed in fruits from trees treated with Zn, IAA, and SA + K + Zn (Figure 3A). These results are consistent with earlier studies on citrus [22], as well as research on guava [40], peach [41], pomegranate [42], and plum [43], all of which demonstrated the positive effects of PGRs and nutrients on juice quality. Citric acid concentration decreased with Zn or Zn + K application across all orchards, with the lowest levels recorded in plants treated with SA + K + Zn, while control plants had the highest citric acid concentration (Figure 3B). Additionally, the foliar application of PGRs and nutrients increased the ascorbic acid content of the juice (Figure 3C). The TSS/acid ratio also increased with the application of Zn and K, either alone or in combination, across all experimental sites (Figure 3D). These findings are supported by the literature, such as [44], who found that applying 2,4-D, GA3, and NAA at flowering improved juice ascorbic acid content, EC, TSS/acid ratio, yield, and quality in 'Kinnow' mandarin. Similarly, previous observations carried out by [45,46] demonstrated that PGR and nutrient foliar sprays enhance juice TSS, ascorbic acid content, and the TSS/acid ratio.

In the present study, juice nutrient contents (N, P, K) were significantly improved by the application of PGRs and nutrients (K and Zn). Potassium plays a vital role in several physiological processes in citrus fruit, including cell division, protein synthesis, growth, organic acid neutralization, and the formation of starch and sugars [47]. Due to its importance, citrus fruit contains relatively high potassium levels compared to other nutrients [48]. Potassium also enhances fruit size, flavor, and color [49]. These findings are consistent with previous studies, such as [50], which showed that foliar application of Zn

and K increased the uptake of macronutrients (N, K, P, Ca) and micronutrients (Fe, B, Zn, Mn) in *Citrus reticulata*. The synergistic interactions between elements like P, K, N, Ca, and Zn may account for the observed increase in nutrient levels following the foliar application of plant growth regulators (SA and IAA) and nutrients (K and Zn). This is supported by previous studies, including [51], which reported an increase in juice N, P, and K content in 'Kinnow' mandarin, and [52], which found enhanced mineral content in Aonla fruit. The current findings further confirm the effectiveness of PGR and nutrient applications, resulting in significant increases in juice potassium (Figure 3A), phosphorus (Figure 3B), and nitrogen (Figure 3C). Among the orchards, the fruits from Sargodha had the highest N, P, and K content, followed by those from Layyah and Faisalabad.

Statistical analyses such as ANOVA (Table 2), PCA (Figure 4), GGE biplot (Figure 5), and the MGIDI (Figure 6) are essential in determining the most suitable treatments for citrus cultivation at the selected sites. PCA helps identify variability and interactions among traits, while the GGE biplot reveals superior treatments across different locations [53]. The novel MGIDI, in particular, assists in selecting the best treatment for achieving higher citrus productivity. Our findings related to juice quality and quantity parameters, coupled with site-specific analysis, enable the identification of the optimal location for producing superior-quality fruits, considering the variation in traits influenced by both site and treatment combinations.

The use of plant growth regulators (SA and IAA) and nutrients (K and Zn) led to significant improvements in citrus fruit characteristics, including shape index (fruit size), peel thickness, fruit retention, reduced fruit drop, fruit weight, juice volume, and juice quality parameters such as EC, TSS, ascorbic acid, and TSS/acid ratio [54]. Variations in these parameters between sites were attributed to differences in soil texture, soil nutrient status, climatic conditions, and irrigation water quality [55]. However, at all selected sites, the combined application of growth regulators and nutrients (SA, Zn, K) consistently resulted in significant enhancements across all parameters.

5. Conclusions

This study, conducted across three citrus orchards in Punjab, Pakistan (Layyah, Faisalabad, and Sargodha), concludes that the foliar application of potassium (K) and zinc (Zn) at 100 mg/L each, combined with salicylic acid (SA) at 100 mg/L and indole acetic acid (IAA) at 5 mg/L, significantly enhanced citrus tree performance regarding fruit and juice quality parameters. Applied either individually or in combination at key growth stages, these treatments reduced fruit drop, leading to improved fruit retention. Significant improvements were also observed in fruit weight, size, peel thickness, juice volume, and quality metrics such as electrical conductivity (EC), total soluble solids (TSS), ascorbic acid content, and the TSS/acid ratio. Additionally, juice nutrient levels, particularly nitrogen (N), phosphorus (P), and potassium (K), increased due to these treatments. Statistical analyses, including PCA and GGE biplot, identified the most stable and effective treatment, with the SA + K + Zn combination consistently yielding the best results across citrus orchards. While site-specific variations were influenced by differences in soil, climate, and irrigation, this treatment was consistently effective, making it a recommended strategy for boosting citrus fruit yield and juice quality, ultimately enhancing economic returns for growers.

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