

## Synergistic influence of plant growth regulators and micronutrients on mitigation of fruit drop and enhancement of physico-chemical characteristics in Kinnow mandarin

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### ABSTRACT

A field experiment was conducted to investigate the impact of various plant growth regulators (PGRs) in conjunction with micronutrients on fruit drop and the physico-chemical characteristics of Kinnow mandarin. The present study used 14 distinct treatments consisting of PGRs and micronutrients at varying doses with control treatment. The results indicated that the higher fruit retention and lowest pea stage, June and preharvest drop was observed in treatment NAA 40 ppm + ZnSO<sub>4</sub> 0.5% as compared to control treatment. The application of NAA 20 ppm + ZnSO<sub>4</sub> 0.5% exhibited the higher fruit weight and fruit length while higher fruit breadth and fruit volume was observed in Kinnow fruits treated with 2,4-D 20 ppm + ZnSO<sub>4</sub> 0.5% as compared to control untreated fruits. Furthermore, fruits treated with NAA 40 ppm + ZnSO<sub>4</sub> 0.5% demonstrated higher TSS, TA, and ripening index. Similarly, 2,4-D 10 ppm + Borax 0.5% exhibited a highest juice weight, peel weight and rag weight compared to the control treatment. In conclusion among applied treatments, NAA 40 ppm + ZnSO<sub>4</sub> 0.5%, NAA 20 ppm + ZnSO<sub>4</sub> 0.5%, 2,4-D 20 ppm + ZnSO<sub>4</sub> 0.5% and 2,4-D 10 ppm + Borax 0.5% was shown to be the most effective to mitigate fruit drop and enhance the physico-chemical characteristics of Kinnow mandarin.

**Keywords:** Auxin, Citrus, Fruit quality, Fruit taste, Ripening index.

### INTRODUCTION

In the citriculture industry of Pakistan, 'Kinnow' mandarin (*Citrus reticulata* Blanco) is a significant fruit for its production and export share. The annual global production of citrus comprises 133.9 million tonnes (FAOSTAT, 2024). Citrus is a significant fruit crop cultivated across all provinces in Pakistan. In 2023-2024, the area cultivation of citrus was 155.9 thousand hectares, with a production volume of 2.3 million tons. Pakistan ranks 12<sup>th</sup> globally in citrus production (MNFSR, 2025).

Kinnow mandarin fruit is regarded as a substantial source of non-enzymatic antioxidants, minerals, and provitamin A (Ali et al., 2021). The dietary benefit is well-known for having a wide range of nutrients (macro and micro) and dietary fibres. These constituents are valued for their ability to uphold a sustainable and nutritious way of life (Kowalska et al., 2023). Potential health advantages include antibacterial, antiviral, anti-inflammatory, and anticancer properties. Citrus juice is also helpful for diabetics. It also has an abundance of fibres that aid the body to remove of harmful compounds (Ahmed and Azmat, 2019). It is eaten in both fresh and processed states owing to its distinctive sweet and acidic taste (Nazir et al., 2023).

Among citrus, growers favour cultivating Kinnow for its excellent yield potential and attractive quality, which provides considerable profit. Despite its profitability and nutritional value, its farming suffers from fruit drop (Nawaz et al., 2008). Kinnow fruit drops throughout the development stages are typical, with considerable reductions at specific intervals. However, preharvest fruit drop is most important, as it causes substantial financial loss for producers (Ashraf et al., 2012). At that stage, the drop of fruit is severe, making up around 50% of the total fruit yield (Nawaz et al., 2008). Fruit drop at various stages may result

### Article History

Received: December 06, 2025, Revised: January 29, 2026,

Accepted: February 10, 2026, First Online: February 20, 2026.



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from fruit fly infestation, pathological issues (stem-end rot), water stress and hormonal dysregulation (Aziz et al., 2020). In Pakistan pre-harvest fruit drop begins in August and remains until the final harvest. Fruit drop arises at the intersection of the peduncle and calyx, lead to in the detachment of the fruit lacking the peduncle. In Pakistan, pre-harvest fruit drop is a major factor influencing to reduced yields in the Kinnow crop (Nawaz et al., 2008). Hormonal dysregulations in the tree, like auxins are essential for growing and retaining fruit. A decline in auxin quantities linked with an increase in abscisic acid quantities causes fruit abscission (Bacelar et al., 2024).

In recent years, scientists worldwide have suggested the application of plant growth regulators (PGRs) to control the fruit drop in Kinnow mandarins. A dysregulation in PGRs such as auxins, cytokinin's, and gibberellins ( $GA_3$ ) initiates the abscission development and results in fruit drop (Moneruzzaman et al., 2011). The 2,4-Dichlorophenoxyacetic acid (2,4-D) it is known for its effectiveness in preventing foliage loss and fruit abscission enhancement in fruits. Among these foliar-supplied auxins significantly alleviated fruit drop in citrus (Aziz et al., 2020). The significance of plant nutrients, particularly zinc in regulating pre-harvest fruit drop. These nutrients are fundamental for ideal plant growth and development, considerably reduced fruit drop and augmentation of fruit market quality. Zinc is crucial element for plant development and biological functions (Khan et al., 2020). Similarly, boron is useful in lessening fruit drop as well as essential for cell wall synthesis, sugar translocation and preventing the development of the fruit's abscission layer, hence evidently enhancing fruit set and retention (El-Sharabasy and Ghazzawy, 2019).

Previous findings exhibited that 2,4-D,  $GA_3$ , 1-Naphthaleneacetic acid (NAA) and  $K_2SO_4$ ,  $ZnSO_4$  significantly mitigated fruit drop in Kinnow mandarin

(Hiteshbhai et al., 2023; Bharti et al., 2020; Pooja et al., 2019; Sihag et al., 2019; Dwivedi et al., 2018; Nawaz et al., 2008), *Khasi* mandarin (Singh et al., 2017), sweet orange (Sweety et al., 2018), date palm (El-Sharabasy and Ghazzawy, 2019), mango (Ahmed et al., 2012), rose apple (Moneruzzaman et al., 2011) fruits. The fruit drop in Kinnow mandarin is a complex issue affected by several factors, involving weather circumstances, hormonal dysregulation and nutrition accessibility. Recently, the foliar applications of PGRs such as NAA and 2,4-D, as well as micronutrients, especially zinc and borax have shown efficacy in reducing fruit drop. Hence this study aimed to assess the effects of PGRs combined with micronutrients on mitigating fruit drop and enhancing physico-chemical characteristics in Kinnow mandarin at agro-climatic conditions of Faisalabad, Punjab, Pakistan.

#### MATERIALS AND METHODS

The study was conducted in the orchard of the Horticultural Research Institute, Ayub Agricultural Research Institute, Faisalabad. The study was conducted using a Randomised Complete Block Design (RCBD) including 14 treatments and a control group. Each treatment was performed thrice, with one tree selected as the replication unit. For this study, ten-year-old Kinnow mandarin 45 plants, were selected, all grafted onto uniform rough lemon rootstock of same size and age. All experimental trees were kept under uniform cultural environments. Foliar applications of PGRs combined with micronutrients were administered at three distinct intervals during the growing season: the first dose in July, the subsequent application in August, and the final application in October. Furthermore, NAA and 2,4-D was first dissolved in ethanol, followed by the addition of the necessary amount of water. The control trees were sprayed with normal water. The PGRs combined with micronutrients are used in foliar treatments as follows

T <sub>0</sub> =	Control (water spray)
T <sub>1</sub> =	NAA 20 ppm
T <sub>2</sub> =	NAA 40 ppm
T <sub>3</sub> =	2,4-D 10 ppm
T <sub>4</sub> =	2,4-D 20 ppm
T <sub>5</sub> =	$ZnSO_4$ 0.5%
T <sub>6</sub> =	Borax 0.5 %
T <sub>7</sub> =	NAA 20 ppm + $ZnSO_4$ 0.5%
T <sub>8</sub> =	NAA 40 ppm + $ZnSO_4$ 0.5%
T <sub>9</sub> =	2,4-D 10 ppm + $ZnSO_4$ 0.5%
T <sub>10</sub> =	2,4-D 20 ppm + $ZnSO_4$ 0.5%
T <sub>11</sub> =	NAA 20ppm + Borax 0.5%
T <sub>12</sub> =	NAA 40 ppm + Borax 0.5%
T <sub>13</sub> =	2,4-D 10 ppm + Borax 0.5%
T <sub>14</sub> =	2,4-D 20 ppm + Borax 0.5%

**Pea stage drop (%), june drop (%), preharvest drop (%) and fruit retention (%)**

To assess the fruit drop during the pea stage of Kinnow, one must count the number of fruits at the onset of the pea stage and again at the final stage of the drop period, usually at the start of the "June drop" phase. Select multiple uniform and healthy trees for observation. Select and tag a minimum of five representative fruiting branches from each tree, ensuring coverage from all cardinal directions. Determine the total quantity of fruits present on each marked branch and record this amount. This represents the initial fruit count (IFC). Subsequently, following the drop period, at the start of the "June drop" phase, when the drop fruits measure approximately 5 mm in diameter, record the number of fruits still present on the marked branches. This represents the final fruit count (FFC). Following formula was used to determine the fruit drop for each tagged tree:

$$\text{Pea stage drop (\%)} = \text{IFC} / \text{FFC} \times 100$$

The June drop was determined by counting the dropped fruit at June month divided by the retained fruits from pea stage to end of June phase on four tagged branches. The % of June drop was calculated employing the formula given below:

$$\text{June drop (\%)} = \text{Total number of fruits dropped at June phase} / \text{Total number of fruits retained on branches from pea stage to June phase} \times 100$$

To assess the preharvest, drop the fruits that dropped from the marked branches of trees were note down at seven-day intervals, beginning on 1<sup>st</sup> August and achieving on 15<sup>th</sup> February (Aziz et al., 2020). The ratio of dropped fruits was measured as follows:

$$\text{Preharvest drop (\%)} = \text{Total number of dropped fruits per tree} / \text{Total number of fruits retained on branches at June phase} \times 100$$

To determine the fruit retention on tagged branches of trees were reported prior to harvest of Kinnow fruit. The ratio of retained fruits was computed in formula outlined below:

$$\text{Fruit retention (\%)} = \text{Total number of dropped fruits from June to prior harvest} / \text{Total number of fruits retained on branches from June phase to harvest phase} \times 100$$

**Fruit weight (g), fruit length (cm), fruit breadth (cm) and fruit volume (cc)**

The Kinnow mandarin fruit weight was measured with an automatic weight balance (Setra, BL-4100S, USA) and indicated as g. The Kinnow mandarin fruit length was assessed by employing vernier callipers and presented as cm. From each replication, five matured Kinnow fruits were collected, and their breadth was measured using a vernier calliper. Breadth measurement was obtained from the broadest

midpoint where the highest girth was observed and is represented in cm. The Kinnow fruit volume of five fruits from each replication at random was determined using the water displacement approach. A specified volume of water was measured in a container, into which fruit was subsequently dipped. The volume of liquid displaced was recorded, and the volume of the fruit was determined by subtracting the initial volume from the final volume of water.

**TSS (%), TA (%) and ripening index**

A 2-3 drops of juice from individual fruit were taken to record total soluble solids by using a handheld digital refractometer (ATAGO, RX 5000, Japan). The recorded values of total soluble solids were averaged and expressed in %. Titratable acidity of fruit juice was determined by using protocols adopted by Ayyub et al. (2024). For this purpose, 10 mL of Kinnow fruit juice was added with 20 mL of distilled water, along with 3-4 drops of phenolphthalein indicator in a glass beaker (100 mL). The prepared solution was titrated against 0.1 N solution of NaOH until light pink colour appeared and expressed as %. The ripening index was determined by dividing the TSS value by the TA value from each replication of various treatments.

**Juice weight (%), peel weight (%) and rag weight (%)**

The Kinnow fruits were halved uniformly, and their juice was extracted using a juice extractor. The juice weight was measured using an electronic weight balance, and the % of juice was calculated using the following formula: Juice weight (%) = Juice weight / Fruit weight × 100

The fruit were hand peeled, and the weight of the peels was measured using a electronic weight balance and expressed as percent. Peel weight (%) = Peel weight / Fruit weight × 100. The rag weight of Kinnow fruit was determined by the weight of the interior membranes and core of the fruit that remain after the peel is excised and the segments are detached and expressed as a percentage using the following formula: Rag weight (%) = Rag weight / Fruit weight × 100

**Fruit visual quality and fruit taste (score)**

A panel of five individuals evaluated the fruit visual quality and fruit taste of Kinnow fruit in each replication from ten fruits, assigning scores on a scale from 1 to 9, as detailed by Ayyub et al. (2025). The assessment system consisted of 1 = inedible, 3 = minimal usability, 5 = marginal marketability, 7 = very good quality, and 9 = excellent quality.

**Statistical investigation**

The current study was executed under RCBD arrangements. The data assessment was conducted via Statistix 8.1 (Tallahassee, Florida, USA), applying the one-way analysis of variance technique. The mean

differences among the treatments were assessed using the least significant difference test. The OriginPro 2021 software (Northampton, Massachusetts, USA) was used to determine the association among several characteristics.

## RESULTS

### Pea Stage Drop, June Drop, Preharvest Drop and Fruit Retention

Analysis of the data indicates that the various treatments exhibited highly significant differences in their effects on pea and preharvest fruit drop, while showing no significant differences regarding June drop (Table 1). The lowest pea stage fruit drop (23%), June drop (17.1%), preharvest drop (16%) and higher fruit retention (98.5%) was observed in Kinnow tree treated with NAA 40 ppm + ZnSO<sub>4</sub> 0.5% while the

maximum fruit drop was recorded in untreated control Kinnow fruits tree (Table 1).

### Fruit Weight, Fruit Length, Fruit Breadth and Fruit Volume

The outcomes of the present investigation indicated highly substantial differences for fruit weight and fruit volume, while significant variations were observed for fruit length and non-significant differences for fruit breadth across various treatments applied to Kinnow fruit (Table 1 and 2). The Kinnow tree treated with NAA 20 ppm + ZnSO<sub>4</sub> 0.5% exhibited the higher fruit weight (127.1 g) and fruit length (6.2 cm) compared to the control treatment, respectively (Table 1). Higher fruit breadth (6.7 cm) and fruit volume (6.8 cc) was observed in Kinnow fruits treated with 2,4-D 20 ppm + ZnSO<sub>4</sub> 0.5% as compared to control untreated fruits (Table 2).

Table 1. Influence of PGRs combined with micronutrients on fruit drop and various attributes of Kinnow mandarin.

Treatments	Pea stage drop (%)	June drop (%)	Preharvest drop (%)	Fruit retention (%)	Fruit weight (g)	Fruit length (cm)
Control (water spray)	30.5 <sup>a</sup>	28.1 <sup>a</sup>	6.8 <sup>a</sup>	93.3 <sup>e</sup>	93.4 <sup>f</sup>	5.2 <sup>a</sup>
NAA 20 ppm	28.6 <sup>b</sup>	26.7 <sup>b</sup>	3.2 <sup>b</sup>	96.3 <sup>d</sup>	96 <sup>f</sup>	6.1 <sup>a</sup>
NAA 40 ppm	26.1 <sup>c</sup>	22.3 <sup>b</sup>	2.5 <sup>b-d</sup>	97.1 <sup>cd</sup>	95 <sup>f</sup>	6 <sup>a</sup>
2,4-D 10 ppm	25 <sup>d-g</sup>	22 <sup>b</sup>	1.8 <sup>de</sup>	98 <sup>ab</sup>	109.8 <sup>e</sup>	6 <sup>a</sup>
2,4-D 20 ppm	25 <sup>d-f</sup>	18.6 <sup>b</sup>	1.9 <sup>c-e</sup>	98.3 <sup>a</sup>	109.3 <sup>e</sup>	6 <sup>a</sup>
ZnSO <sub>4</sub> 0.5%	24 <sup>gh</sup>	19.4 <sup>b</sup>	2.3 <sup>c-e</sup>	97.3 <sup>bc</sup>	117.6 <sup>d</sup>	6 <sup>a</sup>
Borax 0.5 %	28.3 <sup>b</sup>	26.1 <sup>b</sup>	2 <sup>c-e</sup>	98.4 <sup>a</sup>	119.8 <sup>cd</sup>	6 <sup>a</sup>
NAA 20 ppm + ZnSO <sub>4</sub> 0.5%	25.5 <sup>cd</sup>	20.8 <sup>b</sup>	2.2 <sup>c-e</sup>	98 <sup>ab</sup>	127.1 <sup>a</sup>	6.2 <sup>b</sup>
NAA 40 ppm + ZnSO <sub>4</sub> 0.5%	23 <sup>h</sup>	17.1 <sup>b</sup>	1.6 <sup>e</sup>	98.5 <sup>a</sup>	119 <sup>cd</sup>	6 <sup>a</sup>
2,4-D 10 ppm + ZnSO <sub>4</sub> 0.5%	24.8 <sup>d-g</sup>	20.7 <sup>b</sup>	1.9 <sup>c-e</sup>	98.3 <sup>a</sup>	126.6 <sup>ab</sup>	5.9 <sup>a</sup>
2,4-D 20 ppm + ZnSO <sub>4</sub> 0.5%	25.2 <sup>c-e</sup>	19.5 <sup>b</sup>	2.6 <sup>b-d</sup>	98.3 <sup>ab</sup>	122.6 <sup>bc</sup>	5.9 <sup>a</sup>
NAA 20ppm + Borax 0.5%	24 <sup>fg</sup>	19.9 <sup>b</sup>	2.5 <sup>b-e</sup>	97.7 <sup>a-c</sup>	126.2 <sup>ab</sup>	5.8 <sup>a</sup>
NAA 40 ppm + Borax 0.5%	24.6 <sup>d-g</sup>	18.9 <sup>b</sup>	2 <sup>c-e</sup>	98.3 <sup>a</sup>	120.1 <sup>cd</sup>	5.8 <sup>a</sup>
2,4-D 10 ppm + Borax 0.5%	24.2 <sup>c-g</sup>	19.6 <sup>b</sup>	2.1 <sup>c-e</sup>	97.8 <sup>a-c</sup>	121.8 <sup>c</sup>	5.8 <sup>a</sup>
2,4-D 20 ppm + Borax 0.5%	25.3 <sup>cd</sup>	21.9 <sup>b</sup>	2.6 <sup>bc</sup>	97.7 <sup>a-c</sup>	120.3 <sup>cd</sup>	6 <sup>a</sup>
*Significance	<0.0001	NS	<0.0001	<0.0001	<0.0001	0.0096
LSD = P<0.05	1.02	5.07	0.82	0.85	4.07	0.37

\*The general linear model (GLM) technique of ANOVA was employed to obtain *P* values for various PGRs combined with micronutrients on Kinnow mandarin fruit.

The tabular data, shown as three replicates, with differing letters, signifies substantial variances as determined by the LSD test ( $P \leq 0.05$ ).

Table 2. Influence of PGRs combined with micronutrients on fruit drop and various attributes of Kinnow mandarin.

Treatments	Fruit breadth (cm)	Fruit volume (cc)	Total soluble solids (%)	Tiratable acidity (%)	Ripening index
Control (water spray)	5.5 <sup>a</sup>	5.1 <sup>d</sup>	9.4 <sup>k</sup>	1.2 <sup>i</sup>	7.8 <sup>ab</sup>
NAA 20 ppm	6.3 <sup>b</sup>	6.2 <sup>bc</sup>	10.7 <sup>j</sup>	1.3 <sup>hi</sup>	7.8 <sup>ab</sup>
NAA 40 ppm	6.6 <sup>b</sup>	6.4 <sup>b</sup>	11.2 <sup>i</sup>	1.4 <sup>gh</sup>	7.6 <sup>bc</sup>
2,4-D 10 ppm	6.4 <sup>b</sup>	6.3 <sup>bc</sup>	12.4 <sup>h</sup>	1.5 <sup>f-h</sup>	8.2 <sup>ab</sup>
2,4-D 20 ppm	6.3 <sup>b</sup>	6.3 <sup>b</sup>	13 <sup>g</sup>	1.5 <sup>e-h</sup>	8.4 <sup>ab</sup>
ZnSO <sub>4</sub> 0.5%	6.4 <sup>b</sup>	6.4 <sup>b</sup>	13.7 <sup>f</sup>	1.6 <sup>d-g</sup>	8.3 <sup>ab</sup>
Borax 0.5 %	6.5 <sup>b</sup>	6.2 <sup>bc</sup>	14.6 <sup>de</sup>	1.6 <sup>c-g</sup>	8.7 <sup>ab</sup>
NAA 20 ppm + ZnSO <sub>4</sub> 0.5%	6.3 <sup>b</sup>	6.3 <sup>bc</sup>	15.2 <sup>a-c</sup>	1.7 <sup>cd</sup>	8.6 <sup>ab</sup>
NAA 40 ppm + ZnSO <sub>4</sub> 0.5%	6.3 <sup>b</sup>	6.3 <sup>bc</sup>	15.6 <sup>a</sup>	2.2 <sup>a</sup>	9 <sup>a</sup>
2,4-D 10 ppm + ZnSO <sub>4</sub> 0.5%	6.3 <sup>b</sup>	6.1 <sup>bc</sup>	15.3 <sup>ab</sup>	1.8 <sup>b-d</sup>	8.5 <sup>ab</sup>
2,4-D 20 ppm + ZnSO <sub>4</sub> 0.5%	6.7 <sup>b</sup>	6.8 <sup>a</sup>	14.9 <sup>cd</sup>	1.7 <sup>cd</sup>	8.4 <sup>ab</sup>
NAA 20ppm + Borax 0.5%	6.3 <sup>b</sup>	6.2 <sup>bc</sup>	14.6 <sup>de</sup>	1.7 <sup>c-f</sup>	8.9 <sup>a</sup>
NAA 40 ppm + Borax 0.5%	6.3 <sup>b</sup>	6.4 <sup>b</sup>	14.2 <sup>e</sup>	1.8 <sup>c-e</sup>	6.4 <sup>c</sup>
2,4-D 10 ppm + Borax 0.5%	6.4 <sup>b</sup>	6 <sup>c</sup>	15.1 <sup>bc</sup>	1.8 <sup>bc</sup>	8.1 <sup>ab</sup>
2,4-D 20 ppm + Borax 0.5%	6.2 <sup>b</sup>	6.3 <sup>b</sup>	15 <sup>bc</sup>	2 <sup>ab</sup>	7.5 <sup>bc</sup>
*Significance	NS	<0.0001	<0.0001	<0.0001	0.0467
LSD = $P \leq 0.05$	1.59	0.34	0.42	0.22	1.32

\* The general linear model (GLM) technique of ANOVA was employed to obtain P values for various PGRs combined with micronutrients on Kinnow mandarin fruit.

The tabular data, shown as three replicates, with differing letters, signifies substantial variances as determined by the LSD test ( $P \leq 0.05$ ).

### TSS, TA and Ripening Index

The results of the present research indicated that there were highly significant variations for TSS, Tan and ripening index among various treatments given to the Kinnow trees (Table 2). The Kinnow fruits treated with NAA 40 ppm + ZnSO<sub>4</sub> 0.5% demonstrated higher TSS (15.6%), TA (2.2%), and ripening index (9 ratio), whereas the lowest measurements for TSS (9.4%), TA (1.2%), and ripening index (7.8 ratio),

were observed in control untreated treatment (Table 2).

### Juice Weight, Peel Weight and Rag Weight

The juice weight, peel weight and rag weight showed highly significant statistical results among the applied treatments (Table 3). The treatment 2,4-D 10 ppm + Borax 0.5% exhibited a highest juice weight (58.1%), peel weight (30.6%) and rag weight (32.5%) compared to the control treatment (Table 3).

Table 3. Influence of PGRs combined with micronutrients on fruit drop and various attributes of Kinnow mandarin.

Treatments	Juice weight (%)	Peel weight (%)	Rag weight (%)
Control (water spray)	46.8 <sup>k</sup>	23.8 <sup>h</sup>	21.6 <sup>j</sup>
NAA 20 ppm	49.6 <sup>j</sup>	25.2 <sup>g</sup>	22.5 <sup>i</sup>
NAA 40 ppm	50.4 <sup>ij</sup>	26.3 <sup>fg</sup>	23.4 <sup>h</sup>
2,4-D 10 ppm	51.3 <sup>hi</sup>	25.9 <sup>fg</sup>	23.9 <sup>gh</sup>
2,4-D 20 ppm	52.3 <sup>gh</sup>	26.9 <sup>ef</sup>	24.4 <sup>g</sup>
ZnSO <sub>4</sub> 0.5%	53 <sup>g</sup>	27.1 <sup>ef</sup>	25.6 <sup>f</sup>
Borax 0.5 %	54.3 <sup>f</sup>	27.6 <sup>de</sup>	26.2 <sup>f</sup>
NAA 20 ppm + ZnSO <sub>4</sub> 0.5%	54.8 <sup>ef</sup>	28.5 <sup>cd</sup>	27.4 <sup>e</sup>
NAA 40 ppm + ZnSO <sub>4</sub> 0.5%	55.2 <sup>d-f</sup>	28.5 <sup>cd</sup>	28 <sup>e</sup>
2,4-D 10 ppm + ZnSO <sub>4</sub> 0.5%	55.9 <sup>cd</sup>	30.2 <sup>ab</sup>	29.5 <sup>d</sup>
2,4-D 20 ppm + ZnSO <sub>4</sub> 0.5%	55.6 <sup>c-e</sup>	29.1 <sup>bc</sup>	29.6 <sup>cd</sup>
NAA 20ppm + Borax 0.5%	56.6 <sup>bc</sup>	28.8 <sup>cd</sup>	30.3 <sup>c</sup>
NAA 40 ppm + Borax 0.5%	57.1 <sup>ab</sup>	29.3 <sup>a-c</sup>	31.3 <sup>b</sup>
2,4-D 10 ppm + Borax 0.5%	58.1 <sup>a</sup>	30.6 <sup>a</sup>	32.5 <sup>a</sup>
2,4-D 20 ppm + Borax 0.5%	55.1 <sup>d-f</sup>	30.3 <sup>ab</sup>	31.5 <sup>b</sup>
*Significance	<0.0001	<0.0001	<0.0001
LSD = $P \leq 0.05$	1.01	1.32	0.72

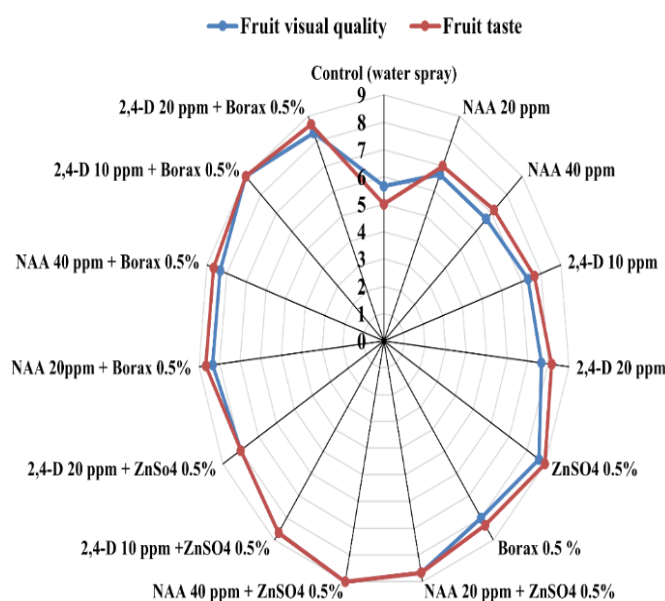
\* The general linear model (GLM) technique of ANOVA was employed to obtain P values for various PGRs combined with micronutrients on Kinnow mandarin fruit.

The tabular data, shown as three replicates, with differing letters, signifies substantial variances as determined by the LSD test ( $P \leq 0.05$ ).

**Fruit Visual Quality and Fruit Taste**

Statistically highly significant changes were observed in treatments regarding the sensory quality attributes such as fruit visual quality and fruit taste of Kinnow fruit. The treatments NAA 40 ppm + ZnSO<sub>4</sub> 0.5% and 2,4-D 10 ppm + Borax 0.5% exhibited a highest fruit

visual quality (9 score) and fruit taste (9 score) of Kinnow fruits compared to the untreated control treatment (Fig. 1).

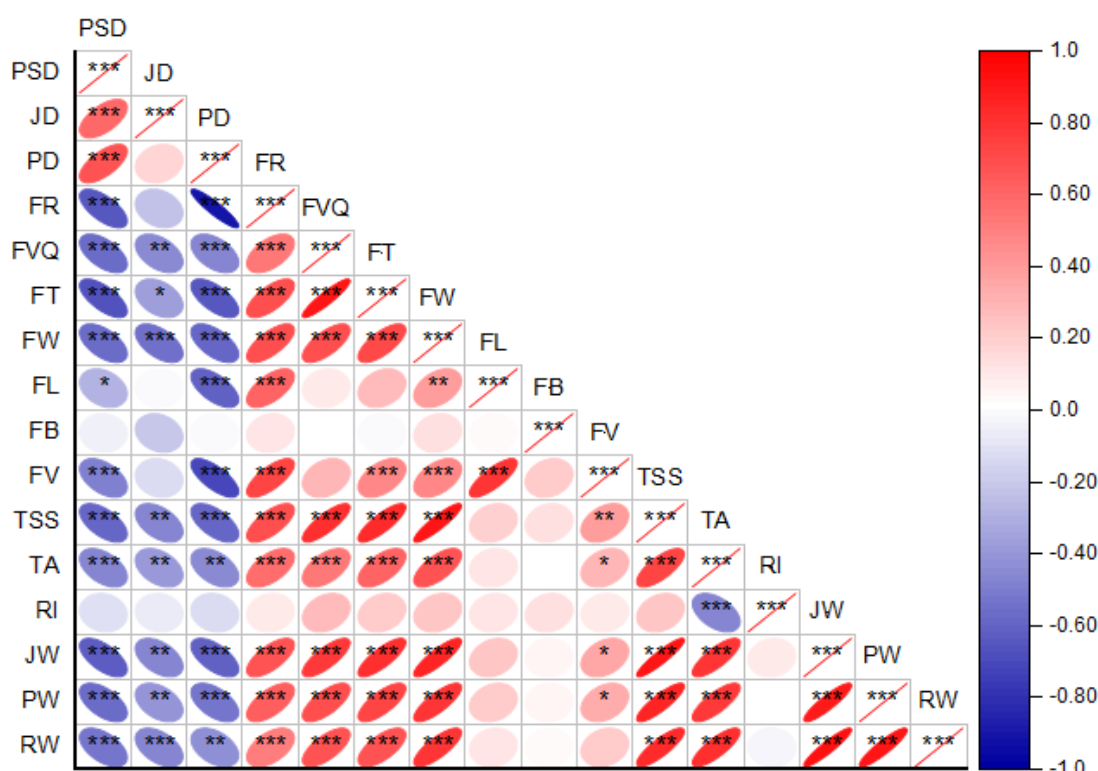


**Figure 1.** Influence of PGRs combined with micronutrients on fruit visual quality and fruit taste of Kinnow mandarin.

### Correlation Investigation

The correlation investigation outcomes demonstrated that FR strong positive associations with FW, FV, JW, and TSS, indicating that decreasing fruit drop concurrently advances fruit size and sweetness. Similarly, FVQ linked with FT, TSS, and RI, representing a concurrent augmentation in sensory and biochemical quality. On the other hand, a substantial negative relationship occurs between fruit drop matrices such as PD, JD, and PSD and most physico-

chemical attributes; for instance, as fruit drop reduces FL, FB, FV, JW and PW increase. Notably, TA exhibited negative correlations with RI and TSS, revealing of the predictable ripening relationship in which acidity declines as sugar levels improve. This complete interaction profile displays that PGRs combined with micronutrient combinations not only downregulate fruit drop but also initiate a sequence of positive quality improvements, enhancing both yield and marketable characteristics of Kinnow mandarin.



**Figure 2.** Correlation of different characteristics as influenced of PGRs combined with micronutrients on Kinnow mandarin. Acronyms: FR = fruit retention, FW = fruit weight, FV = fruit volume, FVQ = fruit visual quality, FT = fruit texture, FB = fruit breadth, FL = fruit length, JW = juice weight, JD = June drop, PD = preharvest drop, PSD = pea stage drop, PW = peel weight, RW = rag weight, RI = ripening index, TSS = total soluble solids and TA = titratable acidity.

### DISCUSSION

Foliar applications of PGRs such as NAA and 2,4-D has shown substantial effectiveness in mitigating fruit drop. These auxins restrain the function of cell wall-breaking enzymes in the abscission layer by sustaining auxin concentrations, consequently inhibiting ethylene-induced senescence and fruit drop (Nawaz et al., 2008; Bharti et al., 2020). Furthermore, micronutrients, like Zinc is essential for the creation of physiological auxins via tryptophan metabolism and serves as a cofactor for many enzymes (Ashraf et

al., 2012). Boron is vital for pollen tube development, fruit formation, cell wall reinforcement, and sugar transfer. Inadequate concentrations in these nutrients increase fruit drop affected by inadequate fruit set and weak pedicel formation (El-Sharabasy and Ghazzawy, 2019). Research consistently indicates that foliar applications of NAA throughout the pea stage and before to harvest considerably decrease drop by enhancing the auxin gradient over the abscission zone in Kinnow mandarin (Nawaz et al., 2008). Likewise, the use of 2,4-D throughout the June drop period and

preharvest increases retention, in part by enhancing fruit vitality and decreasing stress-mediated generation of ethylene in Kinnow mandarin (Bagri et al., 2021). The foliar treatment of ZnSO<sub>4</sub> and Borax during the blooming and pea phases rectifies deficits, promotes fruit cell development and growth, and augments the tree's physiological ability to keep fruits (Ashraf et al., 2012).

The foliar-supplied PGRs, NAA and 2,4-D are essential for enhancing these physical characteristics (weight, length, width, and volume of fruit). Auxins are essential to fruit development by facilitating cell proliferation and expansion, enhancing sink strength, and expanding the transfer of integrates to maturing fruits (Bagri et al., 2021). Concurrently, the ZnSO<sub>4</sub> and Borax, are fundamental for realising genetic capacity in fruit size. Zinc is an essential cofactor for enzymes that facilitate auxin production and carbohydrate metabolism, hence affecting cell division and growth (Ashraf et al., 2012). Boron is required for the structural integrity of cell walls membrane functionality, and the translocation of sugars, a critical mechanism for fruit development. Zinc and boron deficiencies directly restrict cell division, weaken photosynthetic efficiency, and hinder sugar transfer, resulting in small, misshapen fruits (El-Sharabasy and Ghazzawy, 2019). The combined effect of PGRs and micronutrients often results in the most substantial enhancements. The use of NAA or 2,4-D in conjunction with Zn and B enhance fruit development by simultaneously optimising the hormonal regulators of cell expansion and ensuring the nutritional and enzymatic systems for growth are fully operational. Earlier, research demonstrated that integrated sprays may result in a significant enhancement in fruit weight, as well as length, width, and volume, of Kinnow mandarin in comparison to control plants (Bagri et al., 2021; Ashraf et al., 2012; Nawaz et al., 2008).

Augmenting biochemical attributes (TSS, TA and RI) are necessary for producing fruit that meets both fresh-market flavour preferences and processing measures. The use of PGRs substantially affects these biochemical attributes by regulating physiological activities beyond fruit preservation (Singh et al., 2018). PGRs facilitate the translocation of photosynthetic carbohydrates into the expanding fruit, subsequently enhancing sugar increase and advancing TSS. Furthermore, ZnSO<sub>4</sub> and Borax, provide fundamental catalytic and functional in the metabolic pathways that influence fruit quality. Zinc functions as efficient photosynthetic activity and sugar production, promptly accelerating TSS increase (Ashraf et al., 2012). Boron is significant for sugar translocation due to its role in phloem transport and the integrity of cell

membranes. A deficiency of boron impedes the efficient transport of synthesised sugars from leaves to fruits, inhibiting TSS increase (Singh et al., 2018). Additionally, boron contributes to phenol breakdown and events correlated with ripening. Foliar-supplied PGRs and micronutrients during fruit development and pre-harvest stages fix deficits, resultant in higher photosynthesis, upregulated sugar translocation, and more active ripening metabolism, eventually yielding higher TSS and ripening index in Kinnow fruit (Singh et al., 2018; Nawaz et al., 2008).

PGRs noticeably changes the division of incorporates between diverse fruit constituents. Artificial auxins strengthen sink and accelerate the relocation of photo integrates, principally sugars and H<sub>2</sub>O, into the fruit's pulp tissues, therefore improving juice substance and juice weight. ZnSO<sub>4</sub> and Borax are crucial for the biological activities that uphold healthy fruit structure. Appropriate zinc concentrations secure strong photosynthetic activity, contributing the carbohydrates and energy for juice development (Ashraf et al., 2012). A deficiency in borax substantially blocks the transport of sugar into the juice vesicles, causing insufficient juice, a thicker, pithy peel, and additional rag (El-Sharabasy and Ghazzawy, 2019). The pretreatment of PGRs and micronutrients at necessary intervals settles these problems. This indicates to enhanced cell production and increase in the pulp, higher sugar and water juice sacs as well as beneficial, finer peel and rag (Singh et al., 2018). The visual quality and flavour are the principal sensory factors influencing customer choice, marketability, and economic yield for Kinnow mandarin (Khalid et al., 2021). A comprehensive strategy that incorporates PGRs and micronutrients often results in the most substantial synergistic enhancements in overall fruit quality. The PGRs optimise the hormonal milieu to improve fruit retention, sink strength, and ripening synchronisation (Khalid et al., 2021). The micronutrients secure the optimal functioning of the tree's metabolic processes to provide the necessary resources. This combination yields bigger, more aesthetically pleasing fruits that are also abundant in high-quality, flavourful juice in Kinnow fruit (Arshad et al., 2024; Khalid et al., 2021; Prasad et al., 2015).

## CONCLUSION

The study concluded that applications of PGRs combined with micronutrients exhibited mitigated fruit drop alongside enhanced physical (fruit weight, fruit length, fruit volume, juice weight and peel weight) and biochemical (TSS, TA and ripening index) attributes. Additionally, among the applied treatments, NAA 40 ppm + ZnSO<sub>4</sub> 0.5%, NAA 20 ppm + ZnSO<sub>4</sub> 0.5%, 2,4-D 20 ppm + ZnSO<sub>4</sub> 0.5%, and

2,4-D 10 ppm + Borax 0.5% effectively mitigate fruit drop and improve the physico-chemical characteristics of Kinnow mandarin. The correlation investigation showed that effective PGRs coupled with micronutrient, not only lessen fruit drop but also trigger a range of advantageous quality improvements, hence optimising both production and marketable attributes of Kinnow mandarin. Thus, this research highlights the positive effect of PGRs in mitigating fruit drops and advancing physico-chemical characteristics. Conversely, further work on PGRs combined with micronutrients is required to study the molecular and phytochemical mechanisms in Kinnow and across different citrus species.

#### Authors' Contributions

Conceptualization and methodology, M.M. Abbas; software, S. Riaz. and Q.S. Anjum.; validation, N. Shareef. formal analysis, S. Ayyub; investigation, S. Ayyub; resources and data curation, M.M. Abbas. and S. Riaz; writing-original draft preparation, S. Ayyub; writing—review and editing, S. Ayyub. and M. Ali; visualization, S. Ayyub and M. Ali; supervision, M.M. Abbas; project administration, S. Riaz and Q.S. Anjum. All authors have reviewed and consented to the publication of the work.

#### ACKNOWLEDGEMENT

The authors extend their appreciation to the Punjab Agricultural Research Board (PARB) for providing PARB project No. 20-610 entitled “Enhancement of Citrus Nursery Through Germplasm Screening and Mass Multiplication for their Supply to Southern Punjab Areas”.

#### DECLARATIONS

##### Conflict of Interest

The authors assert the lack of any conflict of interest.

##### Funding Information

There was no financial support for this study.

##### Ethical Statement

Not applicable

##### SDG Relevance

SDG goal 2 (Zero Hunger), goal 3 (Good Health and Wellbeing) and 13 (Climate Action)

##### Data Availability

Data will be accessible upon a reasonable request to the corresponding author.

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