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Zinc oxide nanoparticles improve yield and shelf-life of guava (*Psidium guajava* L.)Shivali Sharma\*<sup>◆</sup>, Gaurav Sharma\*, Manish Srivastav\*, Anil Kumar\*\*, Ranjit Pal\*, Ghan Shyam Abrol\* and Raman Choudhary\*

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## Abstract

This study aimed to assess the impact of foliar applied zinc oxide nanoparticles on yield, shelf-life, and organoleptic quality of guava (*Psidium guajava* L.) varieties L-49 and Lalit under subtropical conditions over two consecutive years (2023-2024 & 2024-2025). A factorial randomized block design with three replications was employed to evaluate seven treatments including control, zinc sulphate at 5,000 and 7,500 ppm, zinc oxide nanoparticles at 100, 150, 200, and 250 ppm, applied at flowering and one month after flowering. Results indicated that zinc oxide nanoparticles treatments, particularly at 200-250 ppm, significantly enhanced fruit set (75.35%), retention (75.83%), yield per tree (9.35 kg/tree) and hectare (15.58 t/ha), and extended postharvest shelf-life. The variety L-49 treated with 200 ppm zinc oxide nanoparticles ( $V_1N_3$ ) recorded the highest yield (9.35 kg/tree; 15.58 t/ha), maximum retention, minimal fruit drop, and best marketable retention (40.55% at day 12). The findings offer an eco-friendly and efficient strategy to boost guava yield and postharvest quality. Whereas improved fruit quality and shelf-life can reduce postharvest losses and increase farmer income. This study provides novel insights into genotype × nanonutrition interactions, supporting the sustainable use of nano-fertilizers for enhanced fruit production and postharvest management.

## 1. Introduction

Guava (*Psidium guajava* L.) belonging to the Myrtaceae family is a popular and commercially important fruit tree also known as the Apple of the Tropics or Poor Man's Apple due to its nutritional importance. It has chromosome number  $2n = 2X = 22$  and is native to Central and South America and it is one of the most significant fruit crops in tropical and subtropical regions (Liu *et al.*, 2023) which can be cultivated successfully upto a height of 5000 feet from the mean sea level. The fruit is rich in pectin, lycopene, polyphenols, sugars, minerals, calories (Anand *et al.*, 2020), vitamin C (upto 299 mg/100 g of edible portion), dietary fibre (6.9%), and other nutritional components like vitamin A, riboflavin, thiamine, calcium, phosphorus, and iron (Kumar *et al.*, 2024). At present, the leading guava growing countries of the world are India, China, Thailand, Pakistan, Mexico, Indonesia, Brazil, and Bangladesh. Guava is India's fifth most important fruit crop, after mango, banana, citrus, and papaya. According to the National Horticulture Board's database for 2021-22, India cultivates guava over an area of 3,08,090 hectares, yielding approximately 4,582.30 thousand metric tonnes, with a productivity of 14.87 metric tonnes per hectare (Anonymous, 2022). Though, it is widely cultivated in homestead gardens in India, even with little or no care, but it is commercially grown in the states of Uttar Pradesh,

Andhra Pradesh, Bihar, Madhya Pradesh, West Bengal, Gujarat, Punjab, Maharashtra, and Karnataka. The expanding global population and heightened consumer demand for high quality, nutrient rich fruits have underscored the importance of optimizing both yield and postharvest longevity of perishable commodities like guava (Saputra *et al.*, 2023; Odetayo *et al.*, 2022). In recent years, nanotechnology has emerged as a transformative approach in horticultural production and postharvest management (Handford *et al.*, 2015). The application of zinc oxide nanoparticles as foliar sprays represents a major advancement over conventional fertilization methods, offering efficiency in nutrient delivery, enhanced absorption, and targeted physiological effects (Mehta *et al.*, 2024). Zinc is an essential micronutrient fundamental to plant metabolic processes, including auxin production, enzyme activation and membrane integrity, all of which contribute to optimal fruit development, yield, and quality attributes (Ahmed *et al.*, 2023).

Studies have highlighted that foliar application of ZnO-NPs increases fruit set, retention and yield in several horticultural crops by improving vegetative growth, photosynthetic efficiency, and reproductive success (Saini, 2020; Pippal *et al.*, 2019). In guava specifically, zinc treatments not only boost yield but also positively affect quality parameters such as fruit weight, vitamin C content, and firmness (Laware *et al.*, 2014). Furthermore, nano-enabled coatings and foliar applications have been shown to extend shelf-life and postharvest stability by reducing physiological weight loss, inhibiting microbial decay, and maintaining sensory characteristics, thereby minimizing postharvest losses and ensuring superior marketable quality (Arshad

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and Ali, 2016). The integration of nanozinc technology in guava cultivation for varieties like L-49 and Lalit provides a promising route to address challenges of nutrient deficiency, low productivity and short shelf-life. However, the selection of appropriate nanoparticle concentrations and understanding their long-term environmental implications remain critical for sustainable horticulture (Handford *et al.*, 2015). This research aims to systematically evaluate the influence of foliar-applied zinc oxide nanoparticles on the yield and shelf-life properties of guava varieties L-49 and Lalit, providing scientific evidence to support the adoption of nanotechnology in modern fruit production systems. The study is significant as it addresses critical challenges in guava cultivation, including improving fruit quality, extending postharvest shelf-life and enhancing nutrient use efficiency. By exploring the potential of nano-fertilizers, this work contributes to sustainable horticultural practices and offers strategies for higher productivity and marketable yield in subtropical regions.

## 2. Materials and Methods

### 2.1 Experimental site and plant material

The study was conducted during two years 2023-2024 and 2024-2025 seasons at the Department of Fruit Science, Rani Lakshmi Bai Central Agricultural University, Jhansi, India. The site is located at 25.31°N latitude, 78.33°E longitude, and 285 m above mean sea level, with a sandy loam soil texture. Six-years-old uniform guava trees from two cultivars, Lucknow-49 and Lalit, were used. Trees were spaced at 2×3 following standard orchard practices and maintained under recommended cultural management.

**Lucknow-49:** Tree is vigorous, spreading and profuse bearer, heavy branching type with flat crown. Fruit is large, round to ovate in shape, primrose-yellow skin colour, white flesh and seeds are in plenty.

**Lalit:** It is a high yielding pink fleshed guava variety released by Central Institute for Subtropical Horticulture, Lucknow. Fruits are of saffron yellow colour with red blush. Its flesh is firm and pink with a good blend of sugar and acid. It is suitable for both table and processing purposes. The jelly made from this variety has better flavour and attractive appearance.

### 2.2 Treatment details

A factorial randomized block design (RBD) with three replications was adopted. Treatments consisted of seven foliar nutrient applications, including various concentrations of ZnSO<sub>4</sub> (5000 and 7500 ppm) and nano ZnO (100, 150, 200, and 250 ppm) alongside a control (no zinc treatment). Treatments were randomly assigned within each replication. Foliar sprays were prepared by dispersing ZnO nanoparticles in distilled water, with doses accurately measured per treatment. Sprays were applied using a hand-held sprayer to ensure uniform coverage of the tree canopy. Foliar sprays were timed at full flowering and one month after flowering (mrig bahar).

### 2.3 Yield parameters

#### 2.3.1 Fruit set (%)

Four branches per plant were randomly selected and tagged in each treatment and in each replication. The total number of flowers per shoot were counted starting from initiation till the completion of flowering. The number of flowers set into fruits were counted for

every four days. The fruit setting percent was calculated by using the following formula:

Fruit set percentage

$$= \frac{\text{Number of flowers set into fruits per shoot}}{\text{Total number of flowers per shoot}} \times 100$$

#### 2.3.2 Fruit drop (%)

The fruit drop per cent was calculated by the following formula:

$$\frac{\text{Total number of fruits set} - \text{Total number of harvested fruits at maturity}}{\text{Total number of fruit set}} \times 100$$

#### 2.3.3 Fruit retention (%)

The fruit retention (at maturity) was calculated in per cent using the formula given below:

$$\text{Fruit retention (\%)} = \frac{\text{Total number of fruits harvested}}{\text{Total number of fruit set}} \times 100$$

#### 2.3.4 Fruit yield/tree (kg)

The total number of fruits per tree was multiplied by the average fruit weight to get the average fruit production per tree, which was measured in kilogrammes per tree.

#### 2.3.5 Yield per hectare (tonnes)

Total yield per hectare was calculated by multiplying the hectare factor to the yield per tree and mentioned in tonnes.

### 2.4 Shelf-life assessment

#### 2.4.1 Physiological loss in weight (%)

The initial fruit weight was recorded for five fully matured fruits in each treatment and in each replication with the help of electric top pan balance. Thereafter, the fruit weight was recorded in each treatment for every 3 days of storage. At regular intervals, the average of cumulative losses in fruit weight were calculated and expressed as per cent physiological loss in weight by using following formula:

$$\text{PLW} = \frac{w_1 - w_2}{w_1}$$

where,  $w_1$  = initial fruit weight (g),  $w_2$  = fruit weight at respective days after storage (g)

#### 2.4.2 Marketable fruit retained (%)

The guava fruits were harvested at physiological maturity and stored under ambient conditions. At each observation interval (3<sup>rd</sup>, 6<sup>th</sup>, 9<sup>th</sup> and 12<sup>th</sup> day), fruits were visually inspected and sorted. Fruits that remained free from spoilage symptoms such as shrivelling, wrinkling, over-ripening, microbial decay, or mechanical injury were considered marketable. These fruits retained commercial quality in terms of size, colour, firmness, and appearance. The number of marketable fruits was counted and recorded separately. The percentage of marketable fruits retained was calculated using the following formula:

Marketable fruit retained (%)

$$= \frac{\text{(Number of marketable fruits)}}{\text{Total number of fruits}} \times 100$$

### 2.4.3 Unmarketable fruit retained (%)

The spoilage of guava fruit was recorded in terms of percentage. It was observed in the form of shrivelling, wrinkling, over ripening and fruit rots. The spoiled fruits were separated from the good fruits and the spoilage (%) was calculated:

$$\text{Spoilage (\%)} = \frac{\text{Number of spoiled fruits}}{\text{Total number of fruits}} \times 100$$

### ANOVA Table (FRBD)

Source of variation	Degrees of freedom	Sum of squares (SS)	Mean sum of squares (MSS)	F
Replication	3 - 1 = 2	RSS	RMS	RMS/EMS
Nutrient (N)	7 - 1 = 6	NSS	NMS	NMS/EMS
Variety (V)	2 - 1 = 1	VSS	VMS	VMS/EMS
N × V	(7 - 1)(2 - 1) = 6	NVSS	NVMS	NVMS/EMS
Error	(3 - 1)(14 - 1) = 26	ErSS	ErMS	—
Total	3 × 14 - 1 = 41	TSS	—	—

To test the significance of treatment, the calculated value of “F” was compared with tabular value of “F” at 5% level of probability against error degree of freedom.

Standard Error (SE) and Critical Difference (CD):

$$\text{SE (m)} = \sqrt{(\text{EMS} / r)}$$

$$\text{SE (d)} = \sqrt{(2 \times \text{EMS} / r)}$$

$$\text{CD} = \text{SE(d)} \times t \text{ at } 5\%$$

## 3. Results

The application of zinc oxide nanoparticles had a significant influence on all observed yield and shelf-life parameters in guava, with remarkable variation seen between the Lucknow-49 and Lalit varieties, as well as across treatments and years.

## 2.5 Statistical analysis

The data recorded on yield, fruit and quality parameters of guava fruits were statistically analysed by adopting randomised block design with factorial concept as suggested by Panse and Sukhatme (1978). The significance of the treatments was tested through ‘F’ test at 5 per cent level of significance. The critical difference CD was calculated to assess the significance of difference among the different treatments. Skeleton of ANOVA table (FRBD) is mentioned below.

### 3.1 Fruit set (%)

A significant variation in fruit set percentage was observed between the two guava cultivars and among the nano ZnO treatments as shown in Table 1. The cultivar L-49 consistently exhibited higher fruit set than Lalit across both study years, with pooled means of 68.18% and 60.42%, respectively. Among the treatments, foliar application of nano ZnO at 200 ppm (N<sub>5</sub>) resulted in the highest fruit set (69.65%), followed closely by the 250 ppm treatment (N<sub>6</sub>) at 68.12%. The untreated control (N<sub>0</sub>) recorded the lowest fruit set (56.68%). Interaction effects indicated that the combination of L-49 with N5 produced the maximum fruit set (75.35%), while the lowest was observed in L-49 under control treatment (58.63%) as depicted in Figure 1. Data from both experimental years (2023-24 and 2024-25) followed similar and statistically significant trends.

**Table 1: Effect of nano ZnO on fruit set (%), fruit retention (%) and fruit drop (%) of guava**

Treatments	Fruit set (%)			Fruit retention (%)			Fruit drop (%)			
	Variety	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean
V <sub>1</sub>		67.96 <sup>a</sup>	68.40 <sup>a</sup>	68.18 <sup>a</sup>	68.73 <sup>a</sup>	68.15 <sup>a</sup>	68.44 <sup>a</sup>	31.26 <sup>b</sup>	31.85 <sup>b</sup>	31.55 <sup>b</sup>
V <sub>2</sub>		60.87 <sup>b</sup>	59.97 <sup>b</sup>	60.42 <sup>b</sup>	62.25 <sup>b</sup>	62.28 <sup>b</sup>	62.26 <sup>b</sup>	37.74 <sup>a</sup>	37.71 <sup>a</sup>	37.73 <sup>a</sup>
SE (m±)		1.286	1.35	0.93	1.38	1.38	0.98	1.38	1.38	0.98
LSD (p≤0.05)		3.74	3.94	2.65	4.03	4.02	2.78	4.03	4.026	2.78
N <sub>0</sub>		56.67 <sup>b</sup>	56.69 <sup>b</sup>	56.68 <sup>b</sup>	59.45 <sup>b</sup>	59.29 <sup>b</sup>	59.37 <sup>b</sup>	40.55 <sup>a</sup>	40.70 <sup>a</sup>	40.62 <sup>a</sup>
N <sub>1</sub>		63.13 <sup>ab</sup>	62.27 <sup>ab</sup>	62.70 <sup>ab</sup>	64.16 <sup>ab</sup>	63.44 <sup>ab</sup>	63.80 <sup>ab</sup>	35.83 <sup>ab</sup>	36.56 <sup>ab</sup>	36.19 <sup>ab</sup>
N <sub>2</sub>		64.36 <sup>ab</sup>	64.46 <sup>ab</sup>	64.41 <sup>ab</sup>	65.45 <sup>ab</sup>	64.68 <sup>ab</sup>	65.06 <sup>ab</sup>	34.55 <sup>ab</sup>	35.31 <sup>ab</sup>	34.93 <sup>ab</sup>
N <sub>3</sub>		62.65 <sup>ab</sup>	62.62 <sup>ab</sup>	62.64 <sup>ab</sup>	63.45 <sup>ab</sup>	63.28 <sup>ab</sup>	63.36 <sup>ab</sup>	36.54 <sup>ab</sup>	36.72 <sup>ab</sup>	36.63 <sup>b</sup>
N <sub>4</sub>		65.90 <sup>a</sup>	65.94 <sup>a</sup>	65.92 <sup>a</sup>	66.01 <sup>ab</sup>	65.80 <sup>ab</sup>	65.90 <sup>ab</sup>	33.99 <sup>ab</sup>	34.20 <sup>ab</sup>	34.09 <sup>bc</sup>
N <sub>5</sub>		70.04 <sup>a</sup>	69.26 <sup>a</sup>	69.65 <sup>a</sup>	69.17 <sup>a</sup>	69.02 <sup>a</sup>	69.09 <sup>a</sup>	30.83 <sup>b</sup>	30.98 <sup>b</sup>	30.90 <sup>bc</sup>
N <sub>6</sub>		68.18 <sup>a</sup>	68.07 <sup>a</sup>	68.12 <sup>a</sup>	70.76 <sup>a</sup>	70.99 <sup>a</sup>	70.87 <sup>a</sup>	29.23 <sup>b</sup>	29.01 <sup>b</sup>	29.12 <sup>c</sup>
SE (m±)		2.40	2.54	1.74	2.59	2.59	1.83	2.59	2.59	1.83
LSD (p≤0.05)		6.99	7.38	4.965	7.557	7.53	5.20	7.55	7.53	5.20

### 3.2 Fruit retention (%)

Fruit retention followed almost same patterns of fruit set as shown in Table 1 and Figure 2. The L-49 cultivar demonstrated higher fruit retention with a pooled mean of 68.44%, compared to 62.26% in Lalit. Among treatments, the highest retention was achieved with the 250 ppm nano ZnO application ( $N_6$ ), with a mean value of 70.87%, followed by 200 ppm ( $N_5$ ) at 69.09%. The lowest retention was recorded in control plants (59.37%). Notably, the L-49 cultivar treated with  $N_6$  showed the highest fruit retention (75.83%), whereas the L-49 control group had the lowest retention (58.63%) as depicted in Figure 2.

### 3.3 Fruit drop (%)

Significant effects of treatment and cultivar were also evident in fruit drop percentages as shown in table 1 and Figure 3. The L-49 variety recorded lower fruit drop (31.55%) compared to Lalit (37.73%). Application of nano ZnO at 250 ppm ( $N_6$ ) minimized fruit drop (29.12%), closely followed by 200 ppm ( $N_5$ ) at 30.90%. In contrast, the highest fruit drop was observed in the control treatment (40.62%). Among all combinations, the lowest fruit drop was observed in L-49 under  $N_6$  (24.17%), while the highest occurred in Lalit control (41.37%) as depicted in Figure 3.

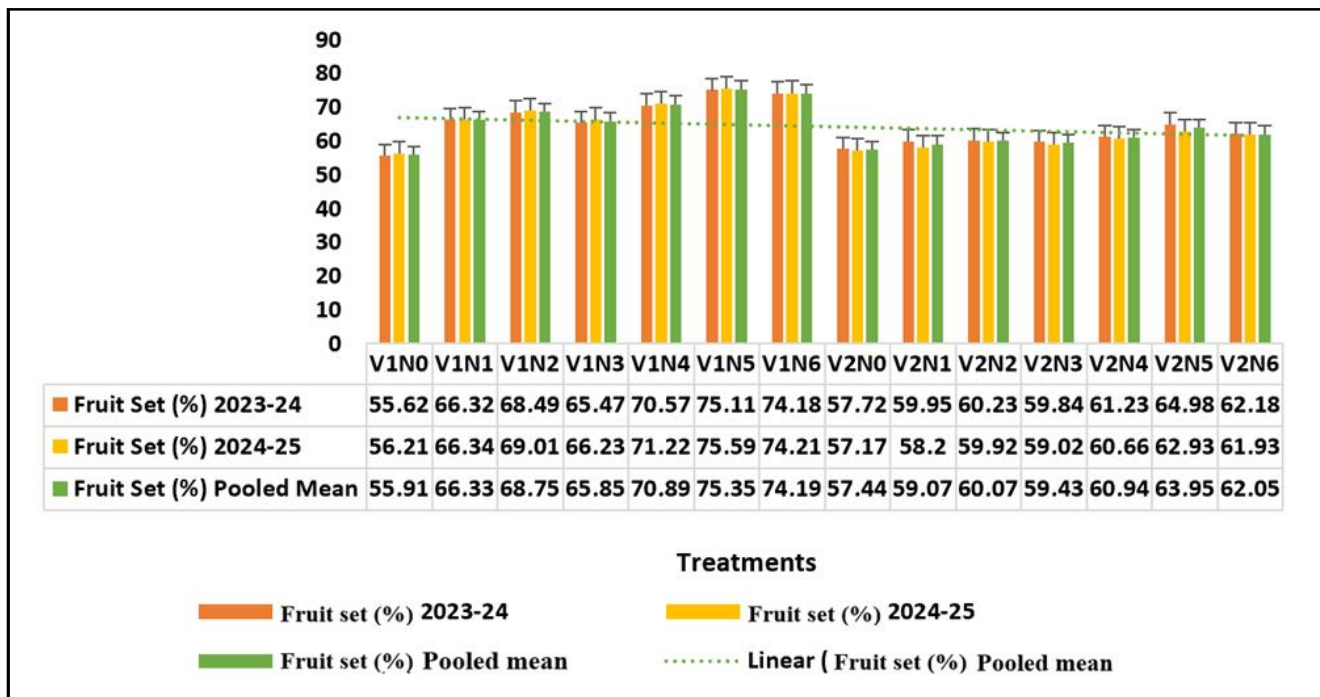


Figure 1: Interaction effect between nutrient and varieties on fruit set of guava.

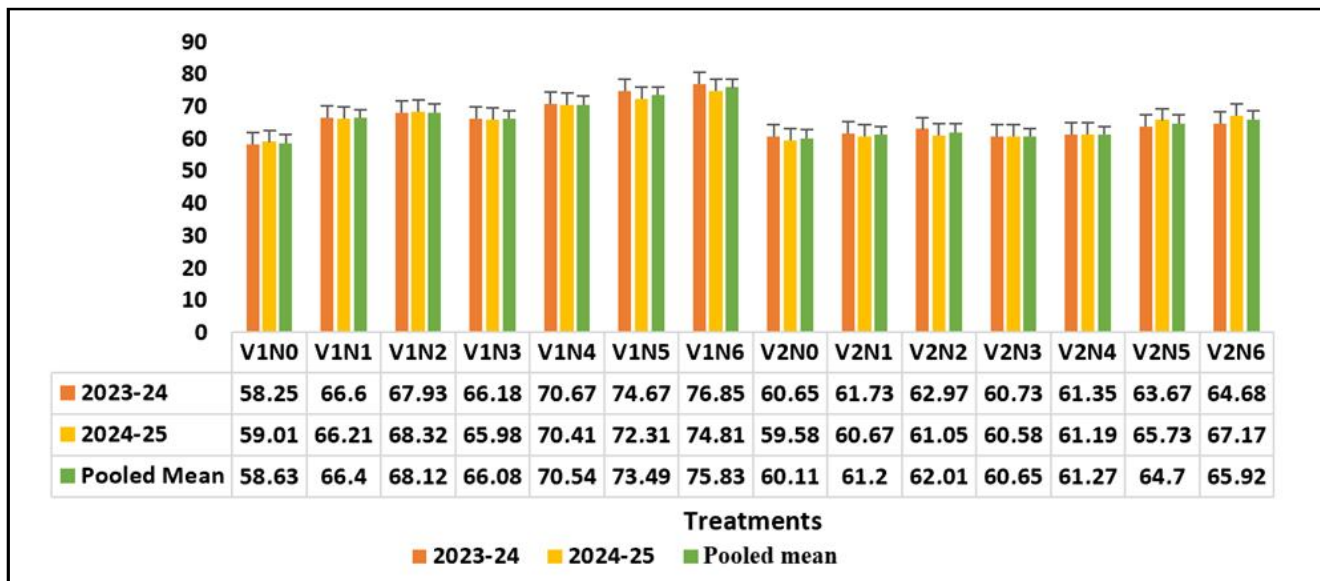


Figure 2: Interaction effect between nutrient and varieties on fruit retention (%) of guava.

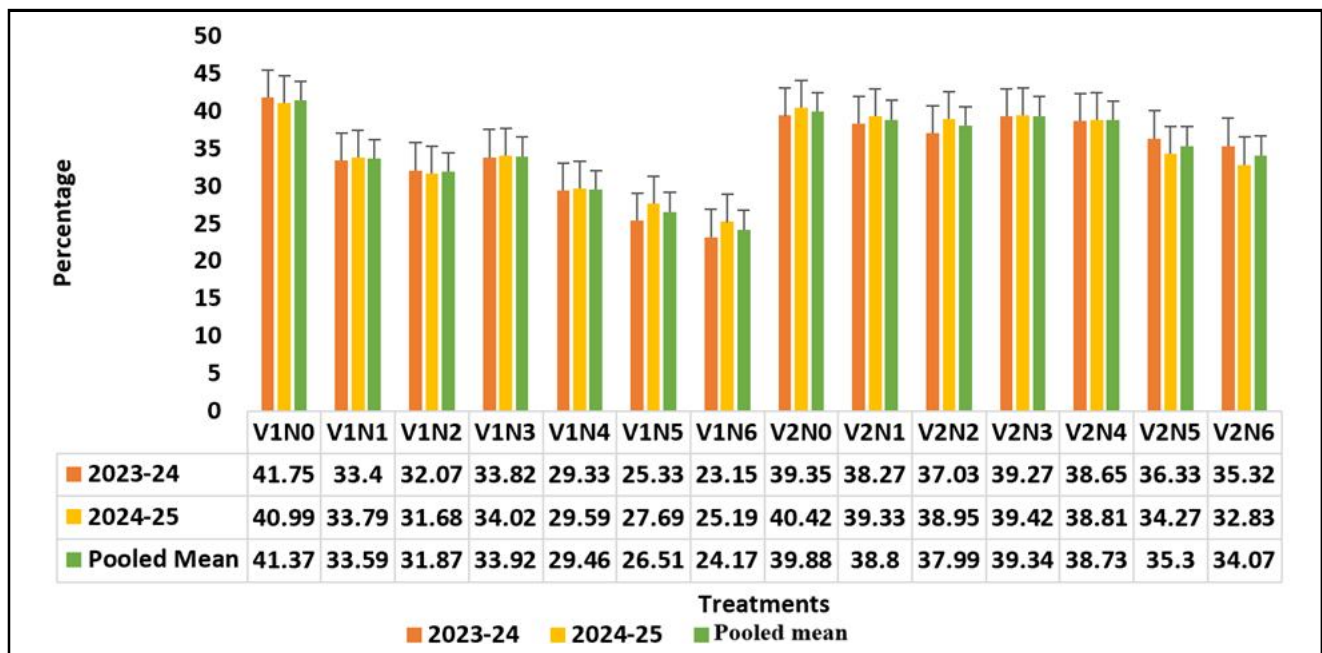


Figure 3: Interaction effect between nutrient and varieties on fruit drop (%) of guava.

### 3.4 Yield (kg/tree and t/ha)

The yield data from two consecutive years (2023-24 and 2024-25) revealed significant effects of both variety and foliar zinc oxide nanoparticle (ZnO NP) treatments on guava fruit production (Tables 2 and 3). Across all treatments, the pooled mean yield per tree was 8.06 kg for variety L-49 and 8.02 kg for Lalit, corresponding to 13.43 t ha and 13.36 t ha, respectively. While the varietal difference was not statistically significant, the application of ZnO NPs resulted in a marked and significant increase in yield compared to the control and traditional  $ZnSO_4$  treatments. The greatest enhancement was observed with the foliar application of ZnO NPs at 200 ppm (N5), which gave the highest pooled mean yield of 9.22 kg tree and 15.37

t ha, closely followed by 250 ppm (N6) with 9.01 kg tree and 15.02 t ha. In contrast, the lowest yields were recorded for the untreated control (6.51 kg tree and 10.86 t ha).

Critically, a highly significant interaction between variety and nutrient treatment was observed. Among all combinations, L-49 treated with 200 ppm ZnO NPs ( $V_1N_5$ ) produced the highest mean yield of 9.35 kg tree in the pooled analysis (15.58 t ha), followed by L-49 at 250 ppm ( $V_1N_6$ ; 9.0 kg tree, 15.07 t ha). Lalit with 200 and 250 ppm ZnO ( $V_2N_5$ ,  $V_2N_6$ ) also produced high yields (9.09 kg tree, 15.16 t ha and 8.99 kg tree, 14.98 t ha, respectively), though marginally lower than L-49. Conversely, the lowest yields were recorded in both varieties under control treatments ( $V_1N_0$  and  $V_2N_0$ ).

Table 2: Effect of nano ZnO on yield (kg/tree) and yield (tonnes/hectare) of guava

Treatments Variety	Yield (kg/tree)			Yield (tonnes/hectare)		
	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean
$V_1$	7.97 <sup>a</sup>	8.15 <sup>a</sup>	8.06 <sup>a</sup>	13.29 <sup>a</sup>	13.57 <sup>a</sup>	13.43 <sup>a</sup>
$V_2$	7.61 <sup>b</sup>	8.07 <sup>a</sup>	8.02 <sup>a</sup>	13.27 <sup>a</sup>	13.46 <sup>a</sup>	13.36 <sup>a</sup>
SE (m±)	0.04	0.03	0.02	0.077	0.06	0.04
LSD ( $p \leq 0.05$ )	0.13	0.10	0.08	0.22	0.17	0.13
$N_0$	6.47 <sup>f</sup>	6.55 <sup>g</sup>	6.51 <sup>g</sup>	10.79 <sup>f</sup>	10.93 <sup>g</sup>	10.86 <sup>g</sup>
$N_1$	7.31 <sup>e</sup>	7.47 <sup>f</sup>	7.39 <sup>f</sup>	12.18 <sup>e</sup>	12.45 <sup>f</sup>	12.31 <sup>f</sup>
$N_2$	8.30 <sup>b</sup>	8.50 <sup>c</sup>	8.40 <sup>c</sup>	13.84 <sup>b</sup>	14.17 <sup>c</sup>	14.00 <sup>c</sup>
$N_3$	7.57 <sup>d</sup>	7.73 <sup>e</sup>	7.65 <sup>e</sup>	12.63 <sup>d</sup>	12.89 <sup>e</sup>	12.76 <sup>e</sup>
$N_4$	7.57 <sup>c</sup>	8.14 <sup>d</sup>	8.07 <sup>d</sup>	13.33 <sup>c</sup>	13.57 <sup>d</sup>	13.45 <sup>d</sup>
$N_5$	9.12 <sup>a</sup>	9.32 <sup>a</sup>	9.22 <sup>a</sup>	15.20 <sup>a</sup>	15.54 <sup>a</sup>	15.37 <sup>a</sup>
$N_6$	7.76 <sup>cd</sup>	9.03 <sup>b</sup>	9.01 <sup>b</sup>	14.99 <sup>a</sup>	15.06 <sup>b</sup>	15.02 <sup>b</sup>
SE (m±)	0.08	0.06	0.05	0.14	0.11	0.09
LSD ( $p \leq 0.05$ )	0.25	0.19	0.15	0.42	0.32	0.26

**Table 3: Interaction effect between nutrient and varieties on yield (kg/tree) and yield (tonnes/hectare) of guava**

Treatment	Yield (kg/tree)			Yield (tonnes/hectare)		
	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean
V <sub>1</sub> N <sub>0</sub>	6.41 <sup>f</sup>	6.51 <sup>i</sup>	6.46 <sup>h</sup>	10.68 <sup>f</sup>	10.86 <sup>i</sup>	10.77 <sup>h</sup>
V <sub>1</sub> N <sub>1</sub>	7.50 <sup>d</sup>	7.71 <sup>g</sup>	7.60 <sup>f</sup>	12.5 <sup>d</sup>	12.85 <sup>g</sup>	12.67 <sup>f</sup>
V <sub>1</sub> N <sub>2</sub>	8.24 <sup>b</sup>	8.42 <sup>cd</sup>	8.33 <sup>cd</sup>	13.73 <sup>b</sup>	14.03 <sup>cd</sup>	13.88 <sup>cd</sup>
V <sub>1</sub> N <sub>3</sub>	7.58 <sup>d</sup>	7.79 <sup>fg</sup>	7.69 <sup>f</sup>	12.65 <sup>d</sup>	12.98 <sup>fg</sup>	12.81 <sup>f</sup>
V <sub>1</sub> N <sub>4</sub>	7.86 <sup>cd</sup>	8.01 <sup>ef</sup>	7.93 <sup>e</sup>	13.1 <sup>cd</sup>	13.35 <sup>ef</sup>	13.22 <sup>e</sup>
V <sub>1</sub> N <sub>5</sub>	9.21 <sup>a</sup>	9.49 <sup>a</sup>	9.35 <sup>a</sup>	15.35 <sup>a</sup>	15.81 <sup>a</sup>	15.58 <sup>a</sup>
V <sub>1</sub> N <sub>6</sub>	9.01 <sup>a</sup>	9.07 <sup>b</sup>	9.0 <sup>b</sup>	15.01 <sup>a</sup>	15.13 <sup>b</sup>	15.07 <sup>b</sup>
V <sub>2</sub> N <sub>0</sub>	6.53 <sup>f</sup>	6.6 <sup>i</sup>	6.56 <sup>h</sup>	10.9 <sup>f</sup>	11.0 <sup>i</sup>	10.95 <sup>h</sup>
V <sub>2</sub> N <sub>1</sub>	7.11 <sup>e</sup>	7.23 <sup>h</sup>	7.17 <sup>g</sup>	11.86 <sup>e</sup>	12.05 <sup>h</sup>	11.95 <sup>g</sup>
V <sub>2</sub> N <sub>2</sub>	8.36 <sup>b</sup>	8.59 <sup>c</sup>	8.48 <sup>c</sup>	13.95 <sup>b</sup>	14.31 <sup>c</sup>	14.13 <sup>c</sup>
V <sub>2</sub> N <sub>3</sub>	7.56 <sup>d</sup>	7.68 <sup>g</sup>	7.62 <sup>f</sup>	12.61 <sup>d</sup>	12.8 <sup>g</sup>	12.70 <sup>f</sup>
V <sub>2</sub> N <sub>4</sub>	8.14 <sup>bc</sup>	8.28 <sup>de</sup>	8.21 <sup>d</sup>	13.56 <sup>bc</sup>	13.8 <sup>de</sup>	13.68 <sup>d</sup>
V <sub>2</sub> N <sub>5</sub>	9.03 <sup>a</sup>	9.15 <sup>b</sup>	9.09 <sup>b</sup>	15.06 <sup>a</sup>	15.26 <sup>b</sup>	15.16 <sup>b</sup>
V <sub>2</sub> N <sub>6</sub>	6.52 <sup>f</sup>	9.0 <sup>b</sup>	8.99 <sup>b</sup>	14.96 <sup>a</sup>	15.0 <sup>b</sup>	14.98 <sup>b</sup>
SE (m±)	0.12	0.09	0.07	0.20	0.15	0.12
LSD (p≤0.05)	0.35	0.27	0.22	0.59	0.46	0.36

### 3.5 Shelf-life

#### 3.5.1 Physiological weight loss (PWL%)

Shelf-life, assessed by physiological weight loss (PWL%) on the 12<sup>th</sup> day after harvest, revealed substantial differences among treatments and cultivars. L-49 fruits exhibited lower PWL (9.11%)

compared to Lalit (9.56%) as shown in Table 4. Application of nano ZnO at 200 ppm (N<sub>5</sub>) resulted in the least weight loss (6.90%), closely followed by 250 ppm (N<sub>6</sub>) at 7.30%. In contrast, control fruits recorded the highest weight loss (13.69%). The lowest PWL was observed in the L-49 × N<sub>5</sub> combination (6.63%), while the highest was recorded in Lalit control (13.95%) as depicted in Table 5.

**Table 4: Effect of nano ZnO on physiological weight loss PWL (%) on 3<sup>rd</sup>, 6<sup>th</sup>, 9<sup>th</sup> and 12<sup>th</sup> day after storage**

Treatment Variety	Physiological weight loss PWL (%)											
	3 <sup>rd</sup> Day			6 <sup>th</sup> Day			9 <sup>th</sup> Day			12 <sup>th</sup> Day		
	2023 -24	2024 -25	Pooled mean	2023 -24	2024 -25	Pooled mean	2023 -24	2024 -25	Pooled mean	2023 -24	2024 -25	Pooled mean
V <sub>1</sub>	2.38 <sup>b</sup>	2.28 <sup>b</sup>	2.33 <sup>b</sup>	4.75 <sup>b</sup>	4.55 <sup>b</sup>	4.65 <sup>b</sup>	8.57 <sup>b</sup>	8.07 <sup>b</sup>	8.32 <sup>b</sup>	9.19 <sup>b</sup>	9.03 <sup>b</sup>	9.11 <sup>b</sup>
V <sub>2</sub>	2.55 <sup>a</sup>	2.45 <sup>a</sup>	2.50 <sup>a</sup>	5.24 <sup>a</sup>	5.04 <sup>a</sup>	5.14 <sup>a</sup>	8.94 <sup>a</sup>	8.68 <sup>a</sup>	8.81 <sup>a</sup>	9.37 <sup>a</sup>	9.75 <sup>a</sup>	9.56 <sup>a</sup>
SE (m±)	0.01	0.01	0.009	0.02	0.02	0.01	0.03	0.05	0.03	0.03	0.05	0.03
LSD (p≤0.05)	0.03	0.04	0.02	0.06	0.08	0.05	0.11	0.14	0.09	0.11	0.16	0.09
N <sub>0</sub>	3.63 <sup>a</sup>	3.55 <sup>a</sup>	3.59 <sup>a</sup>	7.24 <sup>a</sup>	7.04 <sup>a</sup>	7.14 <sup>a</sup>	12.2 <sup>a</sup>	11.74 <sup>a</sup>	11.99 <sup>a</sup>	13.53 <sup>a</sup>	13.86 <sup>a</sup>	13.69 <sup>a</sup>
N <sub>1</sub>	2.90 <sup>b</sup>	2.79 <sup>b</sup>	2.84 <sup>b</sup>	5.75 <sup>b</sup>	5.55 <sup>b</sup>	5.65 <sup>b</sup>	9.75 <sup>b</sup>	9.40 <sup>b</sup>	9.57 <sup>b</sup>	10.47 <sup>b</sup>	10.44 <sup>b</sup>	10.46 <sup>b</sup>
N <sub>2</sub>	2.60 <sup>c</sup>	2.50 <sup>c</sup>	2.55 <sup>c</sup>	5.25 <sup>c</sup>	5.05 <sup>c</sup>	5.15 <sup>c</sup>	9.25 <sup>c</sup>	8.90 <sup>c</sup>	9.07 <sup>c</sup>	9.76 <sup>c</sup>	9.98 <sup>c</sup>	9.87 <sup>c</sup>
N <sub>3</sub>	2.30 <sup>d</sup>	2.20 <sup>d</sup>	2.25 <sup>d</sup>	4.75 <sup>d</sup>	4.55 <sup>d</sup>	4.65 <sup>d</sup>	8.65 <sup>d</sup>	8.29 <sup>d</sup>	8.47 <sup>d</sup>	9.07 <sup>d</sup>	9.20 <sup>d</sup>	9.13 <sup>d</sup>
N <sub>4</sub>	2.05 <sup>e</sup>	1.95 <sup>e</sup>	2.00 <sup>e</sup>	4.25 <sup>e</sup>	4.05 <sup>e</sup>	4.15 <sup>e</sup>	7.65 <sup>e</sup>	7.30 <sup>e</sup>	7.47 <sup>e</sup>	7.94 <sup>e</sup>	8.04 <sup>e</sup>	7.99 <sup>e</sup>
N <sub>5</sub>	1.85 <sup>g</sup>	1.75 <sup>g</sup>	1.80 <sup>g</sup>	3.75 <sup>g</sup>	3.54 <sup>g</sup>	3.64 <sup>g</sup>	6.65 <sup>g</sup>	6.29 <sup>g</sup>	6.47 <sup>g</sup>	6.87 <sup>g</sup>	6.93 <sup>g</sup>	6.90 <sup>g</sup>
N <sub>6</sub>	1.95 <sup>f</sup>	1.85 <sup>f</sup>	1.90 <sup>f</sup>	4.00 <sup>f</sup>	3.79 <sup>f</sup>	3.90 <sup>f</sup>	7.10 <sup>f</sup>	6.70 <sup>f</sup>	6.90 <sup>f</sup>	7.32 <sup>f</sup>	7.28 <sup>f</sup>	7.30 <sup>f</sup>
SE (m±)	0.02	0.02	0.01	0.04	0.05	0.03	0.07	0.09	0.06	0.07	0.10	0.06
LSD (p≤0.05)	0.07	0.07	0.05	0.12	0.15	0.09	0.21	0.27	0.17	0.20	0.31	0.18

**Table 5: Interaction effect between nutrient and varieties physiological weight loss PWL (%) on 3<sup>rd</sup>, 6<sup>th</sup>, 9<sup>th</sup> and 12<sup>th</sup> day after storage**

Treatment	Physiological weight loss PWL (%)											
	3 <sup>rd</sup> Day			6 <sup>th</sup> Day			9 <sup>th</sup> Day			12 <sup>th</sup> Day		
DAS	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean
V <sub>1</sub> N <sub>0</sub>	3.47 <sup>b</sup>	3.40 <sup>b</sup>	3.43 <sup>b</sup>	7.00 <sup>b</sup>	6.80 <sup>b</sup>	6.90 <sup>b</sup>	12.00 <sup>b</sup>	11.49 <sup>b</sup>	11.74 <sup>b</sup>	13.41 <sup>a</sup>	13.47 <sup>b</sup>	13.44 <sup>b</sup>
V <sub>1</sub> N <sub>1</sub>	2.80 <sup>d</sup>	2.69 <sup>d</sup>	2.74 <sup>d</sup>	5.50 <sup>d</sup>	5.30 <sup>d</sup>	5.40 <sup>d</sup>	9.50 <sup>d</sup>	9.00 <sup>d</sup>	9.25 <sup>d</sup>	10.34 <sup>b</sup>	9.89 <sup>e</sup>	10.11 <sup>d</sup>
V <sub>1</sub> N <sub>2</sub>	2.50 <sup>e</sup>	2.40 <sup>e</sup>	2.45 <sup>f</sup>	5.00 <sup>e</sup>	4.80 <sup>e</sup>	4.90 <sup>e</sup>	9.00 <sup>e</sup>	8.50 <sup>e</sup>	8.75 <sup>e</sup>	9.73 <sup>c</sup>	9.55 <sup>ef</sup>	9.64 <sup>e</sup>
V <sub>1</sub> N <sub>3</sub>	2.19 <sup>f</sup>	2.10 <sup>f</sup>	2.14 <sup>h</sup>	4.50 <sup>f</sup>	4.30 <sup>f</sup>	4.40 <sup>f</sup>	8.50 <sup>f</sup>	7.99 <sup>f</sup>	8.24 <sup>f</sup>	9.03 <sup>d</sup>	8.99 <sup>g</sup>	9.01 <sup>f</sup>
V <sub>1</sub> N <sub>4</sub>	2.00 <sup>gh</sup>	1.90 <sup>gh</sup>	1.95 <sup>j</sup>	4.00 <sup>h</sup>	3.80 <sup>gh</sup>	3.90 <sup>h</sup>	7.50 <sup>gh</sup>	7.00 <sup>h</sup>	7.25 <sup>h</sup>	7.95 <sup>e</sup>	7.72 <sup>i</sup>	7.84 <sup>h</sup>
V <sub>1</sub> N <sub>5</sub>	1.80 <sup>i</sup>	1.70 <sup>i</sup>	1.75 <sup>l</sup>	3.50 <sup>j</sup>	3.29 <sup>h</sup>	3.39 <sup>i</sup>	6.49 <sup>k</sup>	5.99 <sup>j</sup>	6.24 <sup>j</sup>	6.68 <sup>h</sup>	6.57 <sup>k</sup>	6.63 <sup>k</sup>
V <sub>1</sub> N <sub>6</sub>	1.90 <sup>hi</sup>	1.80 <sup>hi</sup>	1.85 <sup>k</sup>	3.80 <sup>i</sup>	3.59 <sup>h</sup>	3.70 <sup>i</sup>	7.00 <sup>ij</sup>	6.50 <sup>i</sup>	6.75 <sup>i</sup>	7.19 <sup>fg</sup>	7.01 <sup>jk</sup>	7.10 <sup>j</sup>
V <sub>2</sub> N <sub>0</sub>	3.80 <sup>a</sup>	3.70 <sup>a</sup>	3.75 <sup>a</sup>	7.49 <sup>a</sup>	7.29 <sup>a</sup>	7.39 <sup>a</sup>	12.50 <sup>a</sup>	12.00 <sup>a</sup>	12.25 <sup>a</sup>	13.65 <sup>a</sup>	14.25 <sup>a</sup>	13.95 <sup>a</sup>
V <sub>2</sub> N <sub>1</sub>	3.00 <sup>c</sup>	2.89 <sup>c</sup>	2.94 <sup>c</sup>	6.00 <sup>c</sup>	5.80 <sup>c</sup>	5.90 <sup>c</sup>	10.00 <sup>c</sup>	9.80 <sup>c</sup>	9.90 <sup>c</sup>	10.61 <sup>b</sup>	11.00 <sup>c</sup>	10.80 <sup>c</sup>
V <sub>2</sub> N <sub>2</sub>	2.70 <sup>d</sup>	2.60 <sup>d</sup>	2.65 <sup>e</sup>	5.50 <sup>d</sup>	5.29 <sup>d</sup>	5.39 <sup>d</sup>	9.50 <sup>d</sup>	9.30 <sup>d</sup>	9.40 <sup>d</sup>	9.80 <sup>c</sup>	10.42 <sup>d</sup>	10.11 <sup>d</sup>
V <sub>2</sub> N <sub>3</sub>	2.40 <sup>e</sup>	2.30 <sup>e</sup>	2.35 <sup>g</sup>	5.00 <sup>e</sup>	4.80 <sup>e</sup>	4.90 <sup>e</sup>	8.80 <sup>ef</sup>	8.60 <sup>e</sup>	8.70 <sup>e</sup>	9.10 <sup>d</sup>	9.41 <sup>fg</sup>	9.25 <sup>f</sup>
V <sub>2</sub> N <sub>4</sub>	2.10 <sup>fg</sup>	2.00 <sup>fg</sup>	2.05 <sup>i</sup>	4.50 <sup>f</sup>	4.30 <sup>f</sup>	4.40 <sup>f</sup>	7.80 <sup>g</sup>	7.60 <sup>g</sup>	7.70 <sup>g</sup>	7.93 <sup>e</sup>	8.36 <sup>h</sup>	8.14 <sup>g</sup>
V <sub>2</sub> N <sub>5</sub>	1.90 <sup>hi</sup>	1.80 <sup>hi</sup>	1.85 <sup>k</sup>	4.00 <sup>h</sup>	3.80 <sup>gh</sup>	3.90 <sup>h</sup>	6.80 <sup>i</sup>	6.60 <sup>hi</sup>	6.70 <sup>i</sup>	7.06 <sup>g</sup>	7.28 <sup>ij</sup>	7.17 <sup>j</sup>
V <sub>2</sub> N <sub>6</sub>	1.99 <sup>gh</sup>	1.90 <sup>gh</sup>	1.94 <sup>j</sup>	4.20 <sup>g</sup>	4.00 <sup>g</sup>	4.10 <sup>g</sup>	7.20 <sup>hi</sup>	6.90 <sup>hi</sup>	7.05 <sup>h</sup>	7.46 <sup>f</sup>	7.54 <sup>i</sup>	7.50 <sup>i</sup>
SE (m±)	0.03	0.03	0.02	0.05	0.07	0.04	0.10	0.13	0.08	0.10	0.15	0.09
LSD (p≤0.05)	0.10	0.11	0.07	0.17	0.21	0.13	0.30	0.38	0.24	0.29	0.44	0.26

### 3.5.2 Marketable fruit retention (%)

The percentage of marketable fruits retained on the 12<sup>th</sup> day of storage also varied significantly among treatments and cultivars as shown in Tables 6 and 7. L-49 retained a greater proportion of marketable fruits (20.35%) than Lalit (19.35%). Treatment with nano ZnO at 200 ppm (N5) resulted in the highest retention (40.55%), followed

by 250 ppm (N<sub>6</sub>) at 31.02%. In contrast, control treatments exhibited complete loss of marketable fruits by the twelfth day. The lowest proportion of unmarketable fruits was recorded under N<sub>5</sub> treatment (49.45%), with L-49 × N<sub>5</sub> demonstrating the most favorable outcome (48.60%). On the other hand, control treatments of both cultivars recorded the highest proportion of unmarketable fruits (90%) as shown in Tables 8 and 9.

**Table 6 : Effect of nano ZnO on marketable fruits retained (%) on 3<sup>rd</sup>, 6<sup>th</sup>, 9<sup>th</sup> and 12<sup>th</sup> day after storage**

Treatment	Marketable fruits retained (%)											
	3 <sup>rd</sup> Day			6 <sup>th</sup> Day			9 <sup>th</sup> Day			12 <sup>th</sup> Day		
Variety	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean
V <sub>1</sub>	96.68 <sup>a</sup>	96.49 <sup>a</sup>	96.59 <sup>a</sup>	86.02 <sup>a</sup>	86.57 <sup>a</sup>	86.30 <sup>a</sup>	53.94 <sup>a</sup>	55.29 <sup>a</sup>	54.61 <sup>a</sup>	19.14 <sup>a</sup>	21.55 <sup>a</sup>	20.35 <sup>a</sup>
V <sub>2</sub>	96.23 <sup>a</sup>	96.54 <sup>a</sup>	96.39 <sup>a</sup>	85.07 <sup>a</sup>	85.90 <sup>a</sup>	85.48 <sup>a</sup>	52.77 <sup>b</sup>	53.94 <sup>b</sup>	53.36 <sup>b</sup>	18.14 <sup>b</sup>	20.55 <sup>b</sup>	19.35 <sup>b</sup>
SE (m±)	0.58	0.58	0.41	0.52	0.51	0.36	0.42	0.43	0.30	0.11	0.14	0.09
LSD (p≤0.05)	NA	NA	NA	NA	NA	NA	1.22	1.25	0.85	0.32	0.42	0.26
N <sub>0</sub>	94.75 <sup>a</sup>	94.90 <sup>a</sup>	94.82 <sup>c</sup>	79.00 <sup>f</sup>	79.60 <sup>f</sup>	79.30 <sup>f</sup>	53.50 <sup>g</sup>	56.00 <sup>g</sup>	54.75 <sup>g</sup>	0.00 <sup>g</sup>	0.00 <sup>g</sup>	0.00 <sup>g</sup>
N <sub>1</sub>	95.65 <sup>a</sup>	95.80 <sup>a</sup>	95.72 <sup>bc</sup>	81.75 <sup>ef</sup>	82.30 <sup>ef</sup>	82.02 <sup>ef</sup>	60.75 <sup>f</sup>	62.20 <sup>f</sup>	61.47 <sup>f</sup>	8.50 <sup>f</sup>	10.89 <sup>f</sup>	9.69 <sup>f</sup>
N <sub>2</sub>	96.10 <sup>a</sup>	96.19 <sup>a</sup>	96.15 <sup>abc</sup>	83.99 <sup>de</sup>	84.44 <sup>de</sup>	84.22 <sup>de</sup>	64.50 <sup>e</sup>	65.20 <sup>e</sup>	64.85 <sup>e</sup>	13.49 <sup>e</sup>	16.15 <sup>e</sup>	14.82 <sup>e</sup>
N <sub>3</sub>	96.54 <sup>a</sup>	96.31 <sup>a</sup>	96.43 <sup>abc</sup>	85.85 <sup>cd</sup>	86.80 <sup>cd</sup>	86.32 <sup>cd</sup>	68.25 <sup>d</sup>	69.35 <sup>d</sup>	68.80 <sup>d</sup>	17.50 <sup>d</sup>	20.35 <sup>d</sup>	18.92 <sup>d</sup>
N <sub>4</sub>	96.81 <sup>a</sup>	97.03 <sup>a</sup>	96.92 <sup>abc</sup>	87.75 <sup>bc</sup>	88.45 <sup>bc</sup>	88.10 <sup>bc</sup>	72.24 <sup>c</sup>	73.65 <sup>c</sup>	72.95 <sup>c</sup>	22.50 <sup>c</sup>	25.35 <sup>c</sup>	23.92 <sup>c</sup>
N <sub>5</sub>	97.86 <sup>a</sup>	97.96 <sup>a</sup>	97.91 <sup>a</sup>	91.25 <sup>a</sup>	92.00 <sup>a</sup>	91.62 <sup>a</sup>	83.00 <sup>a</sup>	85.00 <sup>a</sup>	84.00 <sup>a</sup>	39.00 <sup>a</sup>	42.10 <sup>a</sup>	40.55 <sup>a</sup>
N <sub>6</sub>	97.50 <sup>a</sup>	97.42 <sup>a</sup>	97.46 <sup>ab</sup>	89.24 <sup>ab</sup>	90.05 <sup>ab</sup>	89.64 <sup>ab</sup>	78.00 <sup>b</sup>	80.15 <sup>b</sup>	79.07 <sup>b</sup>	29.50 <sup>b</sup>	32.55 <sup>b</sup>	31.02 <sup>b</sup>
SE (m±)	1.09	1.08	0.77	0.98	0.97	0.69	0.79	0.80	0.56	0.20	0.27	0.17
LSD (p≤0.05)	NA	NA	2.19	2.86	2.82	1.96	2.29	2.35	1.60	0.60	0.79	0.48

**Table 7: Interaction effect between nutrient and varieties marketable fruits retained (%) on 3<sup>rd</sup>, 6<sup>th</sup>, 9<sup>th</sup> and 12<sup>th</sup> day after storage**

Treatment	Marketable fruits retained (%)											
DAS	3 <sup>rd</sup> Day			6 <sup>th</sup> Day			9 <sup>th</sup> Day			12 <sup>th</sup> Day		
Interaction effect	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean
V <sub>1</sub> N <sub>0</sub>	95.00 <sup>a</sup>	95.10 <sup>a</sup>	95.05 <sup>a</sup>	80.00 <sup>gh</sup>	80.30 <sup>fg</sup>	80.15 <sup>hi</sup>	55.00 <sup>j</sup>	57.50 <sup>i</sup>	56.25 <sup>h</sup>	0.00 <sup>m</sup>	0.00 <sup>j</sup>	0.00 <sup>m</sup>
V <sub>1</sub> N <sub>1</sub>	95.80 <sup>a</sup>	95.90 <sup>a</sup>	95.85 <sup>a</sup>	82.50 <sup>efg</sup>	82.80 <sup>efg</sup>	82.65 <sup>fgh</sup>	61.50 <sup>hi</sup>	63.20 <sup>gh</sup>	62.35 <sup>fg</sup>	9.00 <sup>k</sup>	11.29 <sup>i</sup>	10.14 <sup>k</sup>
V <sub>1</sub> N <sub>2</sub>	96.20 <sup>a</sup>	96.30 <sup>a</sup>	96.25 <sup>a</sup>	84.49 <sup>cdef</sup>	84.70 <sup>cdef</sup>	84.59 <sup>ef</sup>	65.00 <sup>fg</sup>	65.90 <sup>fg</sup>	65.45 <sup>e</sup>	14.00 <sup>l</sup>	16.50 <sup>h</sup>	15.25 <sup>l</sup>
V <sub>1</sub> N <sub>3</sub>	96.69 <sup>a</sup>	96.13 <sup>a</sup>	96.41 <sup>a</sup>	86.20 <sup>bcd</sup>	87.20 <sup>bcd</sup>	86.70 <sup>cde</sup>	69.00 <sup>de</sup>	70.50 <sup>de</sup>	69.75 <sup>d</sup>	18.00 <sup>g</sup>	20.80 <sup>g</sup>	19.40 <sup>g</sup>
V <sub>1</sub> N <sub>4</sub>	97.30 <sup>a</sup>	96.97 <sup>a</sup>	97.13 <sup>a</sup>	88.00 <sup>abcd</sup>	88.70 <sup>abc</sup>	88.35 <sup>bcd</sup>	73.00 <sup>c</sup>	74.50 <sup>c</sup>	73.75 <sup>c</sup>	22.99 <sup>e</sup>	26.00 <sup>e</sup>	24.49 <sup>e</sup>
V <sub>1</sub> N <sub>5</sub>	98.20 <sup>a</sup>	97.73 <sup>a</sup>	97.96 <sup>a</sup>	91.50 <sup>a</sup>	92.10 <sup>a</sup>	91.80 <sup>a</sup>	83.50 <sup>a</sup>	85.20 <sup>a</sup>	84.35 <sup>a</sup>	40.00 <sup>a</sup>	42.80 <sup>a</sup>	41.40 <sup>a</sup>
V <sub>1</sub> N <sub>6</sub>	97.60 <sup>a</sup>	97.34 <sup>a</sup>	97.47 <sup>a</sup>	89.49 <sup>ab</sup>	90.20 <sup>ab</sup>	89.84 <sup>ab</sup>	78.50 <sup>b</sup>	80.80 <sup>b</sup>	79.65 <sup>b</sup>	30.00 <sup>c</sup>	33.50 <sup>c</sup>	31.75 <sup>c</sup>
V <sub>2</sub> N <sub>0</sub>	94.50 <sup>a</sup>	94.70 <sup>a</sup>	94.60 <sup>a</sup>	78.00 <sup>h</sup>	78.90 <sup>g</sup>	78.45 <sup>i</sup>	52.00 <sup>j</sup>	54.50 <sup>i</sup>	53.25 <sup>i</sup>	0.00 <sup>m</sup>	0.00 <sup>j</sup>	0.00 <sup>m</sup>
V <sub>2</sub> N <sub>1</sub>	95.50 <sup>a</sup>	95.70 <sup>a</sup>	95.60 <sup>a</sup>	81.00 <sup>fgh</sup>	81.80 <sup>fg</sup>	81.40 <sup>gh</sup>	60.03 <sup>i</sup>	61.20 <sup>h</sup>	60.60 <sup>g</sup>	8.00 <sup>l</sup>	10.50 <sup>i</sup>	9.25 <sup>l</sup>
V <sub>2</sub> N <sub>2</sub>	96.00 <sup>a</sup>	96.09 <sup>a</sup>	96.04 <sup>a</sup>	83.49 <sup>defg</sup>	84.19 <sup>def</sup>	83.84 <sup>efg</sup>	64.00 <sup>gh</sup>	64.50 <sup>gh</sup>	64.25 <sup>ef</sup>	12.99 <sup>j</sup>	15.80 <sup>h</sup>	14.40 <sup>j</sup>
V <sub>2</sub> N <sub>3</sub>	96.40 <sup>a</sup>	96.50 <sup>a</sup>	96.45 <sup>a</sup>	85.50 <sup>bcd</sup>	86.4 <sup>bcd</sup>	85.95 <sup>de</sup>	67.50 <sup>ef</sup>	68.20 <sup>ef</sup>	67.85 <sup>d</sup>	17.00 <sup>h</sup>	19.9 <sup>g</sup>	18.45 <sup>h</sup>
V <sub>2</sub> N <sub>4</sub>	96.33 <sup>a</sup>	97.10 <sup>a</sup>	96.71 <sup>a</sup>	87.49 <sup>abcd</sup>	88.20 <sup>abcd</sup>	87.85 <sup>bcd</sup>	71.49 <sup>cd</sup>	72.80 <sup>cd</sup>	72.15 <sup>c</sup>	22.00 <sup>f</sup>	24.7 <sup>f</sup>	23.35 <sup>f</sup>
V <sub>2</sub> N <sub>5</sub>	97.52 <sup>a</sup>	98.20 <sup>a</sup>	97.86 <sup>a</sup>	91.00 <sup>a</sup>	91.90 <sup>a</sup>	91.45 <sup>a</sup>	82.50 <sup>a</sup>	84.80 <sup>a</sup>	83.65 <sup>a</sup>	38.00 <sup>b</sup>	41.40 <sup>b</sup>	39.70 <sup>b</sup>
V <sub>2</sub> N <sub>6</sub>	97.40 <sup>a</sup>	97.50 <sup>a</sup>	97.45 <sup>a</sup>	89.00 <sup>abc</sup>	89.90 <sup>ab</sup>	89.4 <sup>abc</sup>	77.50 <sup>b</sup>	79.50 <sup>b</sup>	78.50 <sup>b</sup>	29.00 <sup>d</sup>	31.6 <sup>d</sup>	30.30 <sup>d</sup>
SE (m±)	1.55	1.53	1.09	1.39	1.37	0.97	1.11	1.14	0.79	0.29	0.38	0.24
LSD (p≤0.05)	NA	NA	NA	4.05	3.99	2.77	3.25	3.32	2.26	0.85	1.119	0.68

**Table 8: Effect of nano ZnO on unmarketable fruits retained (%) on 3<sup>rd</sup>, 6<sup>th</sup>, 9<sup>th</sup> and 12<sup>th</sup> day after storage**

Treatment	Unmarketable fruits (%)											
Variety	3 <sup>th</sup> Day			6 <sup>th</sup> Day			9 <sup>th</sup> Day			12 <sup>th</sup> Day		
	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean
V <sub>1</sub>	3.31 <sup>b</sup>	3.21 <sup>b</sup>	3.26 <sup>b</sup>	12.97 <sup>b</sup>	12.42 <sup>b</sup>	12.70 <sup>b</sup>	25.64 <sup>b</sup>	23.91 <sup>b</sup>	24.78 <sup>b</sup>	70.85 <sup>a</sup>	68.44 <sup>a</sup>	69.65 <sup>a</sup>
V <sub>2</sub>	3.60 <sup>a</sup>	3.45 <sup>a</sup>	3.52 <sup>a</sup>	13.92 <sup>a</sup>	13.10 <sup>a</sup>	13.51 <sup>a</sup>	27.14 <sup>a</sup>	25.64 <sup>a</sup>	36.39 <sup>a</sup>	71.85 <sup>a</sup>	69.44 <sup>a</sup>	70.65 <sup>a</sup>
SE (m±)	0.02	0.02	0.01	0.07	0.06	0.05	0.21	0.20	0.14	0.43	0.44	0.31
LSD (p≤0.05)	0.07	0.06	0.04	0.21	0.20	0.14	0.61	0.58	0.41	NA	NA	NA
N <sub>0</sub>	5.25 <sup>a</sup>	5.10 <sup>a</sup>	5.17 <sup>a</sup>	19.00 <sup>a</sup>	19.39 <sup>a</sup>	19.20 <sup>a</sup>	41.50 <sup>a</sup>	38.99 <sup>a</sup>	40.24 <sup>a</sup>	90.00 <sup>a</sup>	80.00 <sup>a</sup>	85.00 <sup>a</sup>
N <sub>1</sub>	4.35 <sup>b</sup>	4.19 <sup>b</sup>	4.27 <sup>b</sup>	17.24 <sup>b</sup>	16.70 <sup>b</sup>	16.97 <sup>b</sup>	34.25 <sup>b</sup>	32.80 <sup>b</sup>	33.52 <sup>b</sup>	81.50 <sup>b</sup>	79.09 <sup>b</sup>	80.30 <sup>b</sup>
N <sub>2</sub>	3.90 <sup>c</sup>	3.79 <sup>c</sup>	3.84 <sup>c</sup>	15.03 <sup>c</sup>	14.55 <sup>c</sup>	14.77 <sup>c</sup>	30.50 <sup>c</sup>	29.80 <sup>c</sup>	30.15 <sup>c</sup>	76.49 <sup>c</sup>	73.84 <sup>c</sup>	75.17 <sup>c</sup>
N <sub>3</sub>	3.45 <sup>d</sup>	3.35 <sup>d</sup>	3.40 <sup>d</sup>	13.15 <sup>d</sup>	12.20 <sup>d</sup>	12.67 <sup>d</sup>	26.75 <sup>d</sup>	25.65 <sup>d</sup>	26.20 <sup>d</sup>	72.49 <sup>d</sup>	69.64 <sup>d</sup>	71.07 <sup>d</sup>
N <sub>4</sub>	2.85 <sup>e</sup>	2.79 <sup>e</sup>	2.82 <sup>e</sup>	11.25 <sup>e</sup>	10.55 <sup>e</sup>	10.90 <sup>e</sup>	22.74 <sup>e</sup>	21.35 <sup>e</sup>	22.04 <sup>e</sup>	67.49 <sup>e</sup>	64.65 <sup>e</sup>	66.07 <sup>e</sup>
N <sub>5</sub>	1.90 <sup>g</sup>	1.70 <sup>g</sup>	1.80 <sup>g</sup>	7.74 <sup>g</sup>	7.00 <sup>g</sup>	7.376 <sup>g</sup>	12.00 <sup>g</sup>	9.99 <sup>g</sup>	11.00 <sup>g</sup>	51.00 <sup>g</sup>	47.90 <sup>g</sup>	49.45 <sup>g</sup>
N <sub>6</sub>	2.50 <sup>f</sup>	2.40 <sup>f</sup>	2.45 <sup>f</sup>	9.74 <sup>f</sup>	8.95 <sup>f</sup>	9.35 <sup>f</sup>	16.99 <sup>f</sup>	14.85 <sup>f</sup>	15.92 <sup>f</sup>	60.50 <sup>f</sup>	57.45 <sup>f</sup>	58.97 <sup>f</sup>
SE (m±)	0.04	0.04	0.03	0.13	0.12	0.09	0.39	0.37	0.27	0.80	0.83	0.58
LSD (p≤0.05)	0.13	0.12	0.08	0.40	0.37	0.27	1.14	1.09	0.77	2.35	2.42	1.64

**Table 9: Interaction effect between nutrient and varieties on unmarketable fruits retained (%) on 3<sup>rd</sup>, 6<sup>th</sup>, 9<sup>th</sup> and 12<sup>th</sup> day after storage**

Treatment	Unmarketable fruits (%)											
DAS	3 <sup>rd</sup> Day			6 <sup>th</sup> Day			9 <sup>th</sup> Day			12 <sup>th</sup> Day		
Interaction effect	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean	2023-24	2024-25	Pooled mean
V <sub>1</sub> N <sub>0</sub>	5.00 <sup>b</sup>	4.90 <sup>b</sup>	4.95 <sup>b</sup>	19.00 <sup>b</sup>	18.69 <sup>b</sup>	18.85 <sup>b</sup>	40.00 <sup>b</sup>	37.50 <sup>b</sup>	38.75 <sup>b</sup>	90.00 <sup>a</sup>	90.00 <sup>a</sup>	90.00 <sup>a</sup>
V <sub>1</sub> N <sub>1</sub>	4.20 <sup>d</sup>	4.10 <sup>d</sup>	4.15 <sup>d</sup>	16.50 <sup>d</sup>	16.20 <sup>d</sup>	16.35 <sup>d</sup>	33.50 <sup>c</sup>	31.80 <sup>d</sup>	32.65 <sup>d</sup>	81.00 <sup>b</sup>	78.70 <sup>b</sup>	79.85 <sup>b</sup>
V <sub>1</sub> N <sub>2</sub>	3.80 <sup>f</sup>	3.70 <sup>f</sup>	3.75 <sup>f</sup>	14.50 <sup>f</sup>	14.30 <sup>e</sup>	14.40 <sup>f</sup>	30.00 <sup>d</sup>	29.10 <sup>e</sup>	29.55 <sup>f</sup>	76.00 <sup>cd</sup>	73.49 <sup>cd</sup>	74.74 <sup>c</sup>
V <sub>1</sub> N <sub>3</sub>	3.30 <sup>h</sup>	3.20 <sup>h</sup>	3.25 <sup>h</sup>	12.80 <sup>h</sup>	11.80 <sup>g</sup>	12.30 <sup>h</sup>	26.00 <sup>e</sup>	24.50 <sup>g</sup>	25.25 <sup>h</sup>	71.99 <sup>e</sup>	69.19 <sup>e</sup>	70.59 <sup>d</sup>
V <sub>1</sub> N <sub>4</sub>	2.70 <sup>j</sup>	2.70 <sup>j</sup>	2.70 <sup>i</sup>	11.00 <sup>i</sup>	10.30 <sup>h</sup>	10.65 <sup>j</sup>	22.00 <sup>f</sup>	20.50 <sup>i</sup>	21.25 <sup>j</sup>	67.00 <sup>f</sup>	64.00 <sup>f</sup>	65.50 <sup>e</sup>
V <sub>1</sub> N <sub>5</sub>	1.80 <sup>m</sup>	1.60 <sup>n</sup>	1.70 <sup>n</sup>	7.49 <sup>k</sup>	6.90 <sup>j</sup>	7.20 <sup>m</sup>	11.50 <sup>h</sup>	9.80 <sup>k</sup>	10.65 <sup>m</sup>	50.00 <sup>h</sup>	47.20 <sup>h</sup>	48.60 <sup>g</sup>
V <sub>1</sub> N <sub>6</sub>	2.40 <sup>k</sup>	2.30 <sup>l</sup>	2.35 <sup>l</sup>	9.49 <sup>j</sup>	8.80 <sup>i</sup>	9.148 <sup>l</sup>	16.49 <sup>g</sup>	14.20 <sup>j</sup>	15.35 <sup>l</sup>	60.00 <sup>g</sup>	56.50 <sup>g</sup>	58.25 <sup>f</sup>
V <sub>2</sub> N <sub>0</sub>	5.50 <sup>a</sup>	5.30 <sup>a</sup>	5.40 <sup>a</sup>	21.00 <sup>a</sup>	20.09 <sup>a</sup>	20.55 <sup>a</sup>	43.00 <sup>a</sup>	40.49 <sup>a</sup>	41.74 <sup>a</sup>	90.00 <sup>a</sup>	90.00 <sup>a</sup>	90.00 <sup>a</sup>
V <sub>2</sub> N <sub>1</sub>	4.50 <sup>c</sup>	4.29 <sup>c</sup>	4.40 <sup>c</sup>	17.99 <sup>c</sup>	17.20 <sup>c</sup>	17.59 <sup>c</sup>	35.00 <sup>c</sup>	33.80 <sup>c</sup>	34.40 <sup>a</sup>	82.00 <sup>b</sup>	79.49 <sup>b</sup>	80.75 <sup>b</sup>
V <sub>2</sub> N <sub>2</sub>	4.00 <sup>e</sup>	3.89 <sup>e</sup>	3.94 <sup>e</sup>	15.50 <sup>e</sup>	14.80 <sup>e</sup>	15.15 <sup>e</sup>	31.00 <sup>d</sup>	30.50 <sup>de</sup>	30.75 <sup>e</sup>	76.99 <sup>c</sup>	74.20 <sup>c</sup>	75.59 <sup>c</sup>
V <sub>2</sub> N <sub>3</sub>	3.59 <sup>g</sup>	3.50 <sup>g</sup>	3.54 <sup>g</sup>	13.50 <sup>g</sup>	12.60 <sup>f</sup>	13.05 <sup>g</sup>	27.50 <sup>e</sup>	26.80 <sup>f</sup>	28.15 <sup>g</sup>	73.00 <sup>de</sup>	70.10 <sup>de</sup>	71.55 <sup>d</sup>
V <sub>2</sub> N <sub>4</sub>	3.00 <sup>i</sup>	2.89 <sup>i</sup>	2.94 <sup>i</sup>	11.50 <sup>i</sup>	10.80 <sup>h</sup>	11.15 <sup>i</sup>	23.49 <sup>f</sup>	22.20 <sup>h</sup>	22.84 <sup>i</sup>	67.99 <sup>f</sup>	65.30 <sup>f</sup>	66.64 <sup>e</sup>
V <sub>2</sub> N <sub>5</sub>	2.00 <sup>l</sup>	1.80 <sup>m</sup>	1.90 <sup>m</sup>	8.00 <sup>k</sup>	7.103 <sup>j</sup>	7.55 <sup>m</sup>	12.50 <sup>h</sup>	10.19 <sup>k</sup>	11.34 <sup>m</sup>	52.00 <sup>h</sup>	48.60 <sup>h</sup>	50.30 <sup>g</sup>
V <sub>2</sub> N <sub>6</sub>	2.60 <sup>j</sup>	2.50 <sup>k</sup>	2.55 <sup>k</sup>	10.00 <sup>j</sup>	9.103 <sup>i</sup>	9.55 <sup>k</sup>	17.50 <sup>g</sup>	15.49 <sup>j</sup>	16.49 <sup>k</sup>	61.00 <sup>g</sup>	58.40 <sup>g</sup>	59.70 <sup>f</sup>
SE (m±)	0.06	0.06	0.04	0.19	0.18	0.13	0.55	0.53	0.38	1.14	1.17	0.82
LSD (p≤0.05)	0.18	0.17	0.12	0.57	0.53	0.38	1.62	1.55	1.09	3.32	3.42	2.32

#### 4. Discussion

The present study demonstrated that foliar application of zinc oxide nanoparticles significantly influenced key physiological, yield and postharvest traits in guava. Among the different treatments, ZnO NPs at 200 ppm consistently exhibited superior performance, underscoring its efficacy as a nano-nutrient in enhancing fruit production and quality.

The improvement in fruit set percentage observed with ZnO NPs application, particularly at 200 ppm, is attributable to essential role of zinc in reproductive development. This includes enhanced pollen viability, pollen tube growth and hormonal regulation, which collectively contribute to successful fertilization and fruit initiation (Singh *et al.*, 2024). The findings are in agreement (Arora and Singh, 1970), who reported that foliar zinc application significantly improved fruit set in guava. The enhanced efficacy of nano ZnO can be attributed to its smaller particle size and greater surface area, facilitating improved foliar absorption and translocation to reproductive tissues (Arora and Singh, 1970; Baral *et al.*, 2023). A similar trend was observed in fruit retention, where ZnO NP treatments, particularly at 250 ppm, effectively reduced pre-harvest fruit drop and increased retention. This can be explained by involvement of zinc in maintaining cell wall integrity and hormonal balance, especially in modulating auxin and ethylene levels which are critical in abscission processes (Arshad and Ali, 2016; Guo *et al.*, 2024). Previous studies have shown that nano-micronutrient

formulations maintain nutrient supply more efficiently under environmental stress conditions, thereby supporting fruit retention (Verma *et al.*, 2024; Bakshi *et al.*, 2024). The higher fruit retention in variety L-49 under nano ZnO treatment further supports its varietal compatibility with nano-fertilization strategies.

The reduction in fruit drop with ZnO NP treatments corresponds with earlier findings that zinc regulates ethylene biosynthesis, thereby reducing premature abscission (Beniwal *et al.*, 2024). Similar results were reported by Kumar *et al.* (2019), indicating that both ZnSO<sub>4</sub> and nano ZnO treatments decrease fruit drop in guava. The improved nutrient absorption and persistence of ZnO nanoparticles due to their nanometric size enhance zinc availability in plant tissues, contributing to reduced drop rates (Guo *et al.*, 2024). Significant yield enhancement under nano ZnO treatments further validates the role of zinc in promoting physiological efficiency. The highest yields were obtained at 200 ppm ZnO NPs, which can be attributed to improved photosynthesis, assimilate translocation, and nutrient mobilization, all of which are critical for fruit development (Singh *et al.*, 2024). Previous studies have demonstrated that nano-formulations improve zinc bioavailability, enzymatic activity, and metabolic function within the plant system (Guo *et al.*, 2024; Verma *et al.*, 2019), thereby contributing to higher productivity. The results of the present study confirm these observations and emphasize the agronomic and economic advantages of nano ZnO application in guava cultivation.

Postharvest physiological weight loss (PWL) was also significantly reduced by ZnO NP application, with the most effective reduction

observed at 200 ppm. This finding aligns with earlier reports by (Khare *et al.*, 2024) and (Javad *et al.*, 2022), which indicated that ZnO nanoparticles maintain cellular membrane integrity, reduce transpiration, and slow down respiration losses. The ability of ZnO NPs to maintain membrane stability and delay senescence contributes to extended shelf-life and better postharvest performance. Marketable fruit retention was substantially improved under nano ZnO treatments, particularly at 200 ppm, while untreated control fruits showed significant deterioration by the twelfth day of storage. These results are consistent with the findings of (Patel *et al.*, 2022) and (Guo *et al.*, 2024), who reported that ZnO nanoparticles act as a protective agent against microbial infection and enzymatic degradation. ZnO NPs are known to form protective films on fruit surfaces, which reduce microbial ingress, oxidative stress, and moisture loss (Khare *et al.*, 2024; Javad *et al.*, 2022). The superior retention of marketable fruit quality in L-49 under nano ZnO application further indicates varietal responsiveness and the potential for nano ZnO to support postharvest management practices.

The enhancement in quality with ZnO NPs can be attributed to their role in zinc-mediated physiological processes, such as improved photosynthetic efficiency, enzyme activation, and cell wall stabilization (Saini, 2020), which collectively contribute to better fruit development and flavour compound biosynthesis. Zinc's positive influence on sugar and acid metabolism can explain the improvement in taste (Bakshi *et al.*, 2024) whereas its involvement in pigment and aroma compound formation supports the observed improvements in colour, appearance, and flavour (Pippal *et al.*, 2019). The observed improvement in overall acceptability suggests that nano ZnO foliar application not only enhances agronomic and shelf-life parameters but also boosts consumer-oriented quality attributes a promising outcome for both growers and end users. These findings corroborate earlier reports on the efficacy of micronutrient nanoparticles in enhancing fruit texture, colour, and sensory appeal in other fruit crops (Verma *et al.*, 2024).

## 5. Conclusion

This study demonstrates that foliar-applied nano zinc oxide (ZnO) effectively enhances guava productivity and postharvest quality under subtropical conditions. Among seven nutrient treatments, ZnO nanoparticles at 200 ppm consistently improved fruit set, retention, yield, and shelf-life. Genotype-specific responses were observed: Lucknow-49 showed higher yield. Nano ZnO reduced postharvest weight loss and increased marketable fruit retention, likely due to improved foliar absorption, bioavailability, and physiological efficiency over conventional zinc sources. These results highlight the significance of genotype  $\times$  nanonutrient interactions and suggest that 200/ppm nano ZnO is a sustainable, efficient option for guava cultivation. Multi-location and long-term studies are recommended to validate these findings and refine nutrient management strategies.

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## Authors' contribution

Shivali Sharma and Gaurav Sharma conceptualized and designed the research study, Shivali Sharma conducted the experiments, and performed data collection and analysis. Gaurav Sharma supervised the research work and provided overall guidance, Manish Srivastava and Anil Kumar provided scientific guidance and supervised the experimental work throughout the study. Ranjit Pal, Raman Choudhary and Ghanshyam Abrol contributed significantly by assisting with laboratory work, data interpretation, and providing technical support. The research received funding support from RLBCAU University, which facilitated the smooth conductance of the study.

## Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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