

# Gibberellic acid as an eco-friendly treatment for prolonging the shelf-life and maintaining the quality of Siam orange at different maturity stages

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## ABSTRACT

Siam orange (*Citrus nobilis*) is a key horticultural commodity in Indonesia, yet significant postharvest losses (20–50%) due to rapid deterioration pose a major economic and sustainability challenge. Conventional preservation methods often rely on synthetic chemicals with adverse environmental impacts. This study investigated the integrated application of the natural plant growth regulator gibberellic acid (GA<sub>3</sub>) and harvest timing as an eco-friendly strategy to prolong shelf life and maintain quality, aligned with ecological engineering principles. A field experiment employed a Nested Factorial Randomized Block Design with four GA<sub>3</sub> concentrations (0, 25, 50, 75 ppm) and three fruit maturity stages (immature/green, physiologically mature/greenish-yellow, over-mature/yellowish-green). Results demonstrated that pre-harvest GA<sub>3</sub> application, particularly at 50 ppm, combined with harvesting at the physiologically mature stage, acted synergistically to enhance yield, fruit size, and nutritional quality (Vitamin C). Most notably, this combination significantly extended shelf life by approximately 18% (from 16.33 to 19.44 days at ambient storage) and drastically reduced postharvest losses, lowering fungal decay incidence from 42.72% to 15.38% and non-edible matter from 54.78% to around 17–22%. The findings establish that integrating 50 ppm GA<sub>3</sub> with harvest at physiological maturity offers a sustainable, practical protocol. This approach reduces dependency on synthetic postharvest chemicals, minimizes food waste, enhances resource-use efficiency, and contributes to a more resilient and eco-friendly citrus supply chain.

**Keywords:** *Citrus nobilis*, ecological engineering, gibberellic acid, postharvest losses, sustainable agriculture.

## INTRODUCTION

Siam citrus (*Citrus nobilis*) is a popular fruit among various communities due to its pleasant, sweet taste, ease of consumption, economic value, and high nutritional content. Despite its economic importance, the postharvest handling of Siam oranges remains a critical challenge. Substantial losses, often ranging from 20–50%, occur due to rapid quality deterioration and short shelf life, leading to significant economic losses for farmers and distributors (Astiari et al., 2023). These postharvest losses not only represent an economic setback but also contribute to the global issue of food waste, which is a major concern for sustainable

agriculture and resource conservation (Ezeorba et al., 2022; Polipalli et al., 2025). The inefficient use of agricultural inputs and the subsequent waste generated underscore the need for innovative approaches within the framework of ecological engineering to create a more resilient and sustainable food system (Latha and Rajan, 2018).

Conventional postharvest technologies often rely on synthetic chemicals and refrigerated storage to extend shelf life. While effective, these methods raise serious concerns regarding environmental pollution, chemical residues on food, potential health risks, and high energy consumption (Lisboa et al., 2024). The principles of ecological engineering emphasize the design of

sustainable systems that integrate human activities with natural processes to minimize environmental impact (Bergen et al., 2001; Yirmibes et al., 2025). In this context, there is a pressing need to develop eco-friendly alternatives that can reduce dependency on synthetic inputs, minimize the carbon footprint of the supply chain, and enhance the circular economy in agriculture (Kazakova and Lee, 2022).

One promising and sustainable strategy is the pre-harvest application of natural plant growth regulators. Gibberellic acid (GA<sub>3</sub>), a plant-derived hormone, has emerged as a viable, biodegradable, and non-toxic alternative to synthetic compounds (Hedden and Sponsel, 2015). In citriculture, exogenous GA<sub>3</sub> application has been demonstrated to improve fruit set, reduce pre-harvest fruit drop, and enhance various quality parameters such as fruit size and rind colour (Garmendia et al., 2019; Uddin et al., 2024). More importantly from a postharvest perspective, GA<sub>3</sub> plays a crucial role in delaying the senescence process by antagonizing ethylene action, maintaining membrane integrity, and slowing down chlorophyll degradation, thereby directly contributing to an extended shelf life and reduced losses (Lisboa et al., 2024; Khan and Nabi, 2023). The use of such natural bio stimulants aligns perfectly with the goals of ecological engineering by leveraging biological processes to solve practical problems – in this case, postharvest waste – with minimal ecological disruption (Yirmibes et al., 2025).

However, the efficacy of any pre-harvest treatment, including GA<sub>3</sub>, is profoundly influenced by the physiological stage of the crop at harvest. For non-climacteric fruits like Siam orange, which do not ripen significantly after detachment from the plant, harvesting at the optimal maturity stage is paramount (Alfiyandi et al., 2021). The maturity stage dictates the fruit's inherent biochemical composition, which in turn determines its potential shelf life, nutritional quality, and susceptibility to postharvest disorders (Riastana et al., 2019). Harvesting too early results in poor flavour and low nutritional value, while harvesting too late leads to a fruit that is overly soft, more susceptible to pathological attacks, and has a drastically reduced marketable life. Therefore, identifying the precise harvest window is critical for maximizing both quality and postharvest performance.

While the individual effects of GA<sub>3</sub> and harvest timing have been studied to some extent, their synergistic interaction, particularly in the

context of developing an integrated eco-friendly protocol for Siam orange, remains insufficiently explored. Most existing research focuses on yield parameters or standalone postharvest treatments, leaving a gap in understanding how pre-harvest management can be optimized to inherently enhance the fruit's ability to withstand postharvest stresses (Umeohia and Olapade, 2023). Furthermore, there is a lack of studies that frame this integrated approach within the specific principles of ecological engineering, which seek to optimize the entire production system for sustainability.

Therefore, this study was designed to bridge this knowledge gap by systematically investigating the combined effect of pre-harvest GA<sub>3</sub> application and fruit maturity stage at harvest on the shelf life and physicochemical quality of Siam orange. We hypothesize that the integration of an eco-friendly GA<sub>3</sub> treatment with harvesting at a specific physiological maturity stage will act synergistically to significantly prolong shelf life, maintain superior fruit quality, and reduce postharvest losses. The findings of this research aim to provide a sustainable, practical, and ecological engineering-based strategy for farmers and stakeholders in the citrus supply chain, contributing to increased profitability and reduced environmental footprint.

## MATERIALS AND METHODS

### Experimental site and design

The field experiment was conducted over a six-month period from March to September 2025 in Tiga Village, Susut District, Bangli Regency, Bali, Indonesia (elevation 650–800 m above sea level). The site features a cool tropical climate with an average temperature of 15–30 °C and annual rainfall of 2.500–3.500 mm, which is representative of the main Siam citrus production areas in the Indonesian highlands. A Nested Factorial Randomized Block Design (RBD) with three replications was employed to account for field variability and ensure statistical robustness. The first factor was GA<sub>3</sub> concentration, consisting of four levels: 0 ppm (H0, control), 25 ppm (H1), 50 ppm (H2), and 75 ppm (H3). The second factor, fruit maturity stage at harvest, was nested within each GA<sub>3</sub> level and included three stages based on pericarp color development: Mi (immature, shiny green), Mm (physiologically mature, greenish-yellow), and Mo (over-mature, yellowish-green).

This design resulted in 12 treatment combinations, replicated three times, for a total of 36 experimental units.

### Source and application of natural GA<sub>3</sub>

The GA<sub>3</sub> used in this study was a commercially available natural formulation, purchased from a chemical supplier. This product was industrially extracted and purified from fermented cultures of the fungus *Gibberella fujikuroi*, ensuring its eco-friendly and biodegradable nature, which aligns with the principles of sustainable agriculture and ecological engineering (Hedden and Sponsel, 2015; Lisboa et al., 2024). The GA<sub>3</sub> solutions were prepared at concentrations of 0, 25, 50, and 75 ppm using distilled water. Applications were performed via foliar spraying using a handheld sprayer until run-off, three times during the fruit development phase: the first during the rapid fruit growth stage (fruit size equivalent to a ping pong ball), followed by subsequent applications at one-month intervals, with the final spray administered when fruits had reached their maximum size and exhibited a dark green color.

### Agronomic management and treatment integration

All experimental trees received uniform cultural practices and a standardized basal fertilization regimen to isolate the treatment effects. This included the application of 5 kg of composted cow manure, 100 g of Phonska fertilizer (NPK 15-15-15), and 100 g of ZA fertilizer per tree, applied in a circular band around the drip line and incorporated into the soil. This integrated nutrient management approach was implemented to support overall tree health and minimize potential nutrient deficiencies that could confound the results of the GA<sub>3</sub> and maturity stage treatments (Rai et al., 2016). Manual weeding and irrigation were performed as needed to maintain optimal growing conditions.

### Data collection and measurement methods

Data were collected on yield components, l-chemical fruit quality at harvest, and postharvest performance parameters. The number of fruits harvested per tree and the total fruit weight per tree were recorded at each harvest maturity stage. Fruit quality parameters were measured

on a representative sample of fruits from each treatment immediately after harvest. Fruit diameter was measured using a digital caliper, and fruit firmness was determined using a handheld penetrometer (Model FT-327, McCormick Fruit Tech) with an 8-mm tip, expressed in Newton (N), following the method described by Wang et al. (2023). Total soluble solids (TSS) were measured using a digital refractometer (Atago PAL-1) and expressed as °Brix (Luo et al., 2023). Titratable acidity (TA) was determined by titrating fruit juice with 0.1 N NaOH to an endpoint of pH 8.2 and expressed as a percentage of citric acid (Association of Official Analytical Chemists [AOAC, 2016]). Vitamin C (ascorbic acid) content was quantified using the 2,6-dichlorophenolindophenol (DCPIP) titration method and expressed in mg per 100 g of fresh weight (AOAC, 2016).

### Postharvest shelf-life evaluation

To assess postharvest performance, a separate batch of fruits from each treatment was stored at ambient room temperature (25–28 °C) with relative humidity of 75–80%, simulating typical market conditions in the region. The shelf life was determined as the number of days from harvest until the fruits were deemed unmarketable, characterized by visible signs of shriveling, mold development, or a loss of firmness exceeding 50% of the initial value (Alfiyandi et al., 2021). This parameter is critical for evaluating the potential of the treatments to reduce postharvest losses and enhance the sustainability of the supply chain.

### Data tabulation and statistical analysis

All collected data were systematically tabulated and subjected to analysis of variance (ANOVA) appropriate for a nested factorial RCBD using IBM SPSS Statistics version 26. The significance of the main effects (GA<sub>3</sub> concentration and maturity stage) and their interaction was tested at the 5% significance level ( $p < 0.05$ ). In cases where the interaction was found to be significant, treatment means were compared using Duncan's multiple range test (DMRT) to identify significant differences among the treatment combinations. If the interaction was not significant, the main effects were analyzed and reported separately. This comprehensive analytical approach ensured a robust interpretation of the treatment effects on the yield, quality, and shelf life of Siam citrus fruits.

## RESULTS AND DISCUSSION

### Results

#### *Enhanced yield and resource use efficiency*

The application of GA<sub>3</sub> demonstrated a significant positive impact on the yield components of Siam orange trees. GA<sub>3</sub> concentration substantially influenced the number of fruits harvested per tree. The lowest fruit count (122.33 fruits/tree) was observed in the control treatment (0 ppm GA<sub>3</sub>). In contrast, applications of 50 ppm and 75 ppm GA<sub>3</sub> resulted in significantly higher fruit numbers, reaching 150.00 and 153.22 fruits per tree, respectively. This represents a yield increase of 22.6% to 25.2% compared to the untreated control (Table 1). A similar positive trend was observed for the total fruit weight harvested per tree. The control yielded 12.04 kg/tree, while the 50 ppm and 75 ppm GA<sub>3</sub> treatments produced 16.44 kg/tree and 17.23 kg/tree, respectively, indicating a significant enhancement in biomass production. Fruit size, measured by diameter, also responded positively, with the highest values (6.57 cm and 6.58 cm) recorded at 50 ppm and 75 ppm GA<sub>3</sub>, significantly larger than the 6.04 cm observed in the control.

The differential response to fruit maturity stages within each GA<sub>3</sub> concentration revealed important patterns. At 0 ppm GA<sub>3</sub> (H0), the physiologically mature stage (Mm) produced the highest number of fruits (135.67 fruits/tree) and fruit weight per tree (14.13 kg), significantly outperforming the immature stage (Mi), which yielded 108.33 fruits/tree and 9.18 kg. The weight per fruit followed a different pattern, with Mm (101.09 g) and Mo (84.62 g) showing higher values than Mi (71.25 g). At 25 ppm GA<sub>3</sub> (H1), the Mm stage again showed superior performance for fruit weight per tree (18.32 kg) and individual fruit weight (137.71 g), which were significantly higher than at the Mi and Mo stages. The 50 ppm GA<sub>3</sub> (H2) treatment demonstrated that Mm resulted in the highest fruit weight per tree (18.80 kg) and weight per fruit (122.97 g), significantly greater than Mi and Mo. Similarly, at 75 ppm GA<sub>3</sub> (H3), the Mm stage yielded the highest fruit weight per tree (19.19 kg) and weight per fruit (120.47 g), with Mi and Mo showing significantly lower values. This consistent superiority of the Mm stage across all GA<sub>3</sub> concentrations highlights its crucial role in maximizing yield potential.

#### **Fruit quality and nutraceutical enhancement**

The maturity stage emerged as the dominant factor influencing fruit sweetness, measured as TSS. A clear and significant increasing trend in TSS was observed from the immature (Mi) to the over-mature (Mo) stage across all GA<sub>3</sub> concentrations. For instance, under the 75 ppm GA<sub>3</sub> treatment, TSS rose dramatically from a mere 5.87 °Brix in green fruits (Mi) to 8.46 °Brix in physiologically mature fruits (Mm) and further to 9.12 °Brix in over-mature fruits (Mo). Similarly, at 50 ppm GA<sub>3</sub>, TSS increased from 6.00 °Brix (Mi) to 9.16 °Brix (Mm) and 9.58 °Brix (Mo). In contrast, the main effect of GA<sub>3</sub> concentration on TSS was not statistically significant, highlighting that sugar accumulation is predominantly governed by the fruit's developmental progression on the tree.

The maturity stage effect on TSS was consistent across GA<sub>3</sub> concentrations, though with varying magnitudes. At 0 ppm GA<sub>3</sub>, TSS increased from 6.23 °Brix at Mi to 8.12 °Brix at Mo, with Mm showing intermediate values. At 25 ppm GA<sub>3</sub>, the increase was more pronounced, from 5.77 °Brix at Mi to 9.62 °Brix at Mo. The 50 ppm GA<sub>3</sub> treatment showed the most substantial improvement, with TSS rising from 6.00 °Brix at Mi to 9.58 °Brix at Mo. Similarly, at 75 ppm GA<sub>3</sub>, TSS values progressed from 5.87 °Brix at Mi to 9.12 °Brix at Mo. This pattern demonstrates that while GA<sub>3</sub> application doesn't fundamentally alter the TSS accumulation pattern, it may enhance the expression of quality parameters when combined with optimal harvest timing.

The Vitamin C (ascorbic acid) content revealed a more complex relationship with the treatments. GA<sub>3</sub> concentration had a significant main effect, with the 25 ppm treatment resulting in the highest content (164.27 mg/g), which was significantly greater than the control (129.07 mg/g). The maturity stage also exerted a powerful influence, with notable variations within each GA<sub>3</sub> level. At 0 ppm GA<sub>3</sub>, Vitamin C content was highest at the Mm stage (146.67 mg/g), significantly exceeding Mi (111.47 mg/g) and Mo (129.07 mg/g). The 25 ppm GA<sub>3</sub> treatment showed a different pattern, with Mo producing the highest Vitamin C content (199.47 mg/g), significantly greater than Mi (140.80 mg/g) and Mm (152.53 mg/g). At 50 ppm GA<sub>3</sub>, Mo again yielded the highest Vitamin C (176.00 mg/g), followed by Mm (146.67 mg/g) and Mi (129.07 mg/g). The 75 ppm GA<sub>3</sub> treatment showed no significant differences between maturity stages, with

**Table 1.** Effect of harvest maturity stage and GA<sub>3</sub> concentration on yield components and total soluble solids of Siam citrus

Treatment	Number of fruits harvested per tree (fruit)	Weight of fruit harvest per tree (kg)	Weight per fruit (g)	Fruit diameter (cm)	Total soluble solids (°Brix)
GA <sub>3</sub> Concentration					
H <sub>0</sub> (0 ppm)	122.33 c	12.04 c	85.65 b	6.04 c	7.73 a
H <sub>1</sub> (25 ppm)	136.00 b	14.83 b	109.15 a	6.30 b	8.02 a
H <sub>2</sub> (50 ppm)	150.00 a	16.44 a	109.54 a	6.57 a	8.25 a
H <sub>3</sub> (75 ppm)	153.22 a	17.23 a	106.65 a	6.58 a	7.81 a
LSD 5%	12.69	1.55	20.05	0.25	0.53
H0 Concentration					
Mi	108.33 c	9.18 b	84.62 ab	6.03 ab	6.23 c
Mm	123.00 b	12.83 a	71.25 b	6.24 a	8.83 a
Mo	135.67 a	14.13 a	101.09 a	5.84 b	8.12 b
LSD 5%	10.99	1.34	17.36	0.22	0.46
H1 Concentration					
Mi	132.67 a	10.72 c	81.05 c	6.20 b	5.77 c
Mm	133.00 a	18.32 a	137.71 a	6.13 b	8.66 b
Mo	142.33 a	15.44 b	108.69 b	6.57 a	9.62 a
LSD 5%	10.99	1.34	17.36	0.22	0.46
H2 Concentration					
Mi	140.67 b	13.98 c	99.49 b	6.88 a	6.00 b
Mm	153.33 a	18.80 a	122.97 a	6.67 a	9.16 a
Mo	156.00 a	16.54 b	106.17 ab	6.18 b	9.58 a
LSD 5%	10.99	1.34	17.36	0.22	0.46
H3 Concentration					
Mi	155.67 a	16.42 b	101.13 b	6.37 b	5.87 c
Mm	154.00 a	19.19 a	120.47 a	7.05 a	8.46 b
Mo	150.00 a	16.07 b	98.36 b	6.32 b	9.12 a
LSD 5%	10.99	1.34	17.36	0.22	0.46

**Note:** Values followed by the same letter within the same column are not significantly different according to the least significant difference (LSD) test at the 5% level.

values ranging from 140.80 to 152.53 mg/g. This indicates that the optimal combination for maximizing Vitamin C content depends on both GA<sub>3</sub> concentration and harvest timing.

### Eco-friendly shelf-life extension and postharvest loss reduction

The postharvest shelf life of the fruits was significantly extended by GA<sub>3</sub> application, showcasing its potential as an eco-friendly alternative to synthetic postharvest chemicals. The control fruits (0 ppm GA<sub>3</sub>) had the shortest shelf life (16.33 days). In contrast, fruits treated with 25 ppm and 50 ppm GA<sub>3</sub> lasted significantly longer, with shelf lives of 19.22 and 19.44 days, respectively (Table 2). This represents an extension of nearly 3 days, or approximately 18%, compared to the control.

The maturity stage effect on shelf life varied considerably across GA<sub>3</sub> concentrations. At 0 ppm GA<sub>3</sub>, shelf life showed no significant differences between maturity stages, ranging from 14.67 to 17.67 days. However, at 25 ppm GA<sub>3</sub>, the Mm

stage provided the longest shelf life (22.00 days), significantly exceeding both Mi (20.00 days) and Mo (15.67 days). This pattern was even more pronounced at 50 ppm GA<sub>3</sub>, where Mm resulted in a remarkable shelf life of 23.33 days, significantly longer than Mi (14.67 days) and Mo (20.33 days). At 75 ppm GA<sub>3</sub>, the Mm stage again yielded the longest shelf life (22.67 days), significantly superior to Mi (15.67 days) and Mo (15.33 days). This consistent superiority of the Mm stage at higher GA<sub>3</sub> concentrations demonstrates its crucial role in maximizing postharvest longevity.

The application of GA<sub>3</sub> also led to a substantial reduction in postharvest qualitative losses. The incidence of fungal decay was highest in the control (42.72%) and was significantly reduced to 21.31%, 15.38%, and 15.74% with 25, 50, and 75 ppm GA<sub>3</sub>, respectively (Table 2). The maturity stage effect on fungal decay showed interesting patterns within GA<sub>3</sub> levels. At 0 ppm GA<sub>3</sub>, no significant differences were observed between maturity stages, with decay incidence ranging from 42.15% to 43.73%. At 25 ppm GA<sub>3</sub>, Mm showed the lowest decay incidence

(20.95%), significantly lower than Mi (26.66%). The 50 ppm GA<sub>3</sub> treatment demonstrated that Mm and Mo had significantly lower decay incidence (14.28% and 14.88%, respectively) compared to Mi (19.47%). Similarly, at 75 ppm GA<sub>3</sub>, Mm and Mo showed significantly lower decay (15.24% and 17.19%, respectively) than Mi (21.73%). Correspondingly, the proportion of non-edible fruit matter at the end of the storage period was drastically lowered from 54.78% in the control to between 17.89% and 22.05% in the GA<sub>3</sub>-treated fruits. The maturity stage effects mirrored those observed for fungal decay. At 0 ppm GA<sub>3</sub>, Mi resulted in the lowest non-edible matter (45.16%), significantly lower than Mm (54.83%). At 25 ppm GA<sub>3</sub>, Mm showed the lowest values (19.68%), significantly better than Mi (23.27%). The 50 ppm GA<sub>3</sub> treatment demonstrated that Mm had the lowest non-edible matter (16.87%), significantly superior to Mi (18.95%). At 75 ppm GA<sub>3</sub>, Mm again yielded

the best results (15.68%), significantly better than Mi (19.27%). The Mm maturity stage, in particular, was consistently associated with the lowest values for these loss parameters across GA<sub>3</sub> concentrations, underscoring its importance in maintaining fruit integrity during storage.

### Discussion

The comprehensive findings of this study elucidate that the pre-harvest application of GA<sub>3</sub> and the strategic timing of harvest based on fruit maturity constitute powerful, eco-compatible strategies for enhancing the productivity, quality, and postharvest sustainability of Siam orange cultivation. The significant increase in fruit number and weight per tree with GA<sub>3</sub> application, particularly at 50-75 ppm, aligns with the fundamental role of gibberellins in regulating various physiological processes including fruit set, cell division, and source-sink relationships (Lisboa et al., 2024;

**Table 2.** The effect of fruit harvesting based on maturity stage at different GA<sub>3</sub> concentrations on Vitamin C content, fruit shelf life, Incidence of fungal decay and Proportion of non-edible fruit matter at the end of the storage period

Treatment	Fruit Vitamin C Content at harvest (mg/g)	Fruit shelf life (days after harvest)	Incidence of fungal decay at 24 days of storage (%)	Proportion of non-edible fruit matter at the end of the storage period (%)
GA <sub>3</sub> Concentration				
H <sub>0</sub> (0 ppm)	129.07 b	16.33 b	42.72 b	54.78 a
H <sub>1</sub> (25 ppm)	164.27 a	19.22 a	21.31 a	22.05 b
H <sub>2</sub> (50 ppm)	150.58 a	19.44 a	15.38 a	17.89 b
H <sub>3</sub> (75 ppm)	148.62 ab	17.89 ab	15.74 a	18.29 b
LSD 5%	20.04	2.12	6.56	8.65
H0 Concentration				
Mi	129.07 b	17.67 a	43.73 a	54.83 a
Mm	111.47 c	16.67 a	42.15 a	45.16 b
Mo	146.67 a	14.67 a	42.28 a	48.35 ab
LSD 5%	17.35	1.83	1.32	6.54
H1 Concentration				
Mi	140.80 b	20.00 b	26.66 a	23.27 a
Mm	152.53 b	22.00 a	20.95 b	19.68 b
Mo	199.47 a	15.67 c	22.31 ab	21.90 ab
LSD 5%	17.35	1.83	4.62	3.47
H2 Concentration				
Mi	129.07 c	14.67 c	19.47 a	18.95 a
Mm	146.67 b	23.33 a	14.28 b	16.87 b
Mo	176.00 a	20.33 b	14.88 b	17.87 ab
LSD 5%	17.35	1.83	3.62	1.67
H3 Concentration				
Mi	140.80 a	15.67 b	21.73 a	19.27 a
Mm	152.53 a	22.67 a	15.24 b	15.68 b
Mo	152.53 a	15.33 b	17.19 b	16.90 b
LSD 5%	17.35	1.83	4.48	2.5 6

**Note:** Values followed by the same letter within the same column are not significantly different according to the least significant difference (LSD) test at the 5% level.

Uddin et al., 2024). This yield enhancement represents a crucial advancement in ecological engineering approaches, as it demonstrates the potential to maximize resource use efficiency, a cornerstone principle in sustainable agriculture (Kour et al., 2020; Nosheen et al., 2021).

The differential response of yield parameters to maturity stages within each GA<sub>3</sub> concentration reveals important physiological insights. The consistent superiority of the Mm stage across all GA<sub>3</sub> levels for fruit weight per tree and individual fruit weight suggests that physiological maturity represents an optimal balance between fruit development and biochemical maturation. At this stage, fruits have achieved near-maximum size while maintaining sufficient physiological integrity to respond positively to GA<sub>3</sub> applications. The poorer performance of the Mi stage, particularly evident at higher GA<sub>3</sub> concentrations (H2 and H3), indicates that immature fruits lack the physiological capacity to fully utilize the growth-promoting effects of gibberellins. This finding corroborates with studies on other citrus varieties which emphasize that fruit responsiveness to plant growth regulators is highly dependent on developmental stage (Garmendia et al., 2019; Khan and Nabi, 2023).

The profound influence of harvest maturity on fruit quality parameters, particularly TSS, underscores the non-climacteric nature of citrus fruits where quality attributes are predominantly determined on the tree. The progressive increase in TSS from Mi to Mo stages across all GA<sub>3</sub> concentrations reflects the natural accumulation of soluble solids during fruit maturation. Interestingly, the magnitude of this increase was most substantial at 50 ppm GA<sub>3</sub>, suggesting that this concentration might optimize the metabolic processes involved in sugar accumulation without disrupting the natural ripening sequence. This finding aligns with ecological engineering principles that advocate for management practices that work in harmony with natural developmental processes rather than overriding them (Ghazian and Lortie, 2024; Sajjad et al., 2025).

The complex relationship between GA<sub>3</sub> concentration, maturity stage, and Vitamin C content reveals important nuances in nutritional quality enhancement. The exceptional Vitamin C levels in Mo fruits at 25 and 50 ppm GA<sub>3</sub> suggest a synergistic effect where GA<sub>3</sub> application extends the period of active metabolite accumulation typically associated with later maturation stages. This

phenomenon might be explained by GA<sub>3</sub>'s role in delaying senescence processes, thereby prolonging the biosynthetic activity of ascorbic acid pathways (Zhang et al., 2023). However, the absence of this effect at 75 ppm GA<sub>3</sub> indicates a concentration threshold beyond which the potential benefits are diminished, possibly due to hormonal imbalance or accelerated metabolic turnover. This complex interaction highlights the importance of precise dosage and timing in biofortification strategies, a principle increasingly recognized in sustainable fruit production systems (Yuan et al., 2022; Ambarita et al., 2025).

The remarkable extension of shelf life achieved through GA<sub>3</sub> application, particularly when combined with harvest at the Mm stage, represents a significant advancement in sustainable postharvest management. The anti-senescence properties of gibberellins are well-documented, primarily through their antagonistic effects on ethylene biosynthesis and action, maintenance of membrane integrity, and preservation of cell wall structure (Kim et al., 2023; Wang et al., 2023; wang et al., 2025). However, our findings reveal that these benefits are maximized when fruits are harvested at physiological maturity, suggesting that the Mm stage represents an optimal physiological state for responding to GA<sub>3</sub>-mediated preservation mechanisms. The poor shelf life of Mi fruits, even at high GA<sub>3</sub> concentrations, indicates that biochemical immaturity creates limitations that cannot be overcome by growth regulator applications alone.

The substantial reduction in postharvest losses, particularly fungal decay and non-edible matter, through the integrated application of GA<sub>3</sub> and harvest at Mm stage, has profound implications for sustainable food systems. The minimized losses achieved through this approach directly contribute to several Sustainable Development Goals, particularly those related to food security, sustainable consumption, and climate action. The mechanism likely involves GA<sub>3</sub>-induced enhancement of fruit resistance mechanisms, including thicker cuticles, improved cell wall integrity, and potentially induced resistance responses (Shi et al., 2024). The consistent superiority of the Mm stage in minimizing losses across all GA<sub>3</sub> concentrations suggests that fruits at this developmental stage possess optimal structural and biochemical characteristics for withstanding postharvest challenges, a finding that aligns with

integrated pest management principles in ecological engineering (Jain et al., 2023).

The ecological implications of these findings extend beyond immediate quality and shelf life improvements. By reducing dependence on synthetic postharvest chemicals and minimizing food waste, this integrated approach contributes to cleaner production systems with reduced environmental footprint. This aligns perfectly with the growing emphasis on circular economy principles in agriculture, where waste reduction and resource efficiency are paramount (Polipalli et al., 2025). Furthermore, the enhanced nutritional quality achieved through optimized GA<sub>3</sub> and harvest timing contributes to improved food sovereignty and public health outcomes, key considerations in sustainable food system transformations (Oluwole et al., 2023).

When contextualized within the broader framework of ecological engineering, our findings demonstrate how targeted physiological interventions can enhance ecosystem services in agricultural systems. The improved resource use efficiency, reduced waste, and enhanced product quality achieved through this integrated approach contribute to multiple dimensions of sustainability. This aligns with similar advancements in other cropping systems, such as the use of biofilm-forming biofertilizers to enhance nutrient use efficiency in maize (Ambarita et al., 2025) and organic mulches to improve soil health and crop productivity (Sajjad et al., 2025). These complementary approaches collectively illustrate how ecological engineering principles can be applied across different agricultural contexts to enhance sustainability.

## CONCLUSIONS

In conclusion, the pre-harvest application of 50 ppm GA<sub>3</sub> combined with harvesting at the physiologically mature stage (greenish-yellow pericarp) constitutes an effective, eco-friendly, and sustainable strategy aligned with ecological engineering principles for Siam orange production. This integrated protocol synergistically enhances fruit yield and size, improves key quality attributes and drastically reduces postharvest losses from fungal decay and fruit deterioration. The findings underscore that physiological maturity is a critical determinant for maximizing the efficacy of GA<sub>3</sub>, optimizing the fruit's inherent

physiological resilience, resource use efficiency, and postharvest performance. Therefore, it is recommended that citrus growers adopt this specific combination of 50 ppm GA<sub>3</sub> application and harvest timing at physiological maturity as a practical, sustainable alternative to synthetic postharvest chemicals to enhance productivity, minimize food waste, and reduce the environmental footprint of the supply chain. Future research should explore the economic viability of this approach and its integration with other sustainable practices to further enhance the ecological sustainability of citrus production systems.

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