e-ISSN 2581-0405
Asian Journal of Applied Research for Community Development and Empowerment
Journal home page: http://ajarcde-safe-network.org ISSN 2581-0405

Optimizing GA_3 Concentration and Application Timing for Enhanced Parthenocarpy Induction and Fruit Quality in Cucumber (*Cucumis sativus* L.)

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ARTICLE INFO

Article History:
Received: 16 May 2026
Final Revision: 01 June 2026
Accepted: 03 June 2026
Online Publication: 05 June 2026

KEYWORDS

GA_3 concentration, parthenocarpy induction, anthesis timing, cucumber yield, seedless fruit production, plant growth regulators, horticultural crop optimization

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A B S T R A C T

Cucumber is a high-value horticultural crop for which stable fruit set and seedless quality are increasingly in demand in intensive production systems. Parthenocarpy induction using gibberellic acid (GA_3) offers a practical strategy to enhance yield stability and market preference under limited pollination conditions. This study aimed to evaluate the independent and combined effects of GA_3 concentration and application timing on parthenocarpy success, yield components, and fruit quality in greenhouse-grown cucumber. A factorial Completely Randomized Design tested four GA_3 concentrations (0, 100, 200, 300 ppm) and three application timings (pre-anthesis, anthesis, post-anthesis) with three replications. Results revealed that both concentration and timing significantly affected Fruit Set percentage, while their interaction was not significant. Fruit Set increased progressively from control (70.21%) to 300 ppm (87.81%), with anthesis application producing the highest mean Fruit Set (86.97%). Higher GA_3 levels (200–300 ppm) improved fruit weight, diameter, length, and flesh thickness, while substantially reducing seed number. The findings indicate a nonlinear dose–response pattern with a tendency toward saturation at higher concentrations. Optimizing GA_3 concentration and synchronizing its application with anthesis enhances parthenocarpy efficiency, yield, and commercial fruit quality in cucumber production systems.

Contribution to Sustainable Development Goals (SDGs):
SDG 2: Zero Hunger
SDG 8: Decent Work and Economic Growth
SDG 9: Industry, Innovation, and Infrastructure
SDG 12: Responsible Consumption and Production
SDG 13: Climate Action

1. INTRODUCTION

1.1. Research Background

Cucumber (*Cucumis sativus* L.) is a high-value horticultural crop cultivated widely for fresh consumption and processing, and its commercial success increasingly depends on stable fruit set, uniformity, and market-oriented quality traits [1][2]. In intensive production systems, particularly under greenhouse or high-temperature conditions, pollinator limitation and environmental stress can compromise fertilization and reduce yield stability, making alternative strategies to secure fruit set essential [1][3]. Parthenocarpy—the development of fruit without pollination or fertilization—offers a practical solution by ensuring reliable fruit formation even when natural pollination is suboptimal [1][2]. Beyond yield stabilization, parthenocarpic fruits are typically seedless or contain fewer seeds, attributes strongly preferred by consumers and processors, and often associated with improved uniformity and specific quality traits depending on genotype and induction method [4][5][6][7].

The growing demand for seedless fruit in domestic and export markets has accelerated both agronomic and biotechnological innovations aimed at inducing or stabilizing parthenocarpy [8][9].

Exogenous plant growth regulators (PGRs), including auxins, gibberellins (GAs), and cytokinins such as forchlorfenuron (CPPU), are widely deployed to promote seedless or low-seed fruit formation, often in combination with targeted agronomic measures [10][11][12][13]. At the same time, breeding approaches based on quantitative trait loci (QTL) mapping, marker-assisted selection, triploid development, and genome editing are increasingly used to introgress or engineer parthenocarpic capacity in commercial cultivars [1][14][15]. These parallel strategies underscore that consumer demand for seedless fruit is a primary driver of hormone-based management, genetic improvement, and molecular innovation in horticulture [8][9].

Physiologically, parthenocarpy is initiated when the arrested ovary is reprogrammed to enter cell division and expansion in the absence of fertilization, a process primarily mediated by coordinated changes in phytohormone signaling, especially auxin and gibberellins [16][17]. Fertilization or exogenous auxin/GA application triggers large-scale transcriptional reprogramming in maternal ovary tissues, activating genes related to the cell cycle, cell wall modification, and sink strength, which collectively are sufficient to initiate fruit growth without zygote formation [17][18][19]. Other hormones, including cytokinins, brassinosteroids, and jasmonates, can modulate these networks by interacting with auxin–GA crosstalk and influencing the balance between cell division and expansion, thereby shaping fruit size and quality outcomes [4][16][10].

Among these regulators, gibberellic acid (GA_3) plays a central role in promoting early fruit initiation by relieving DELLA-mediated repression of cell division and expansion pathways [20][21]. Exogenous GA increases bioactive GA levels, promotes DELLA degradation via the GID1 receptor pathway, and derepresses transcription factors such as members of the CEB1 and CYP78A families that activate cell cycle and expansion genes in the ovary wall and pericarp [20][22]. Histological and hormonal analyses demonstrate that GA treatments enlarge both cell number and cell size in developing ovaries and enhance sink strength, whereas GA inhibitors or DELLA gain-of-function mutations suppress these responses, confirming GA dependence in parthenocarpic fruit initiation [23][24][20]. However, GA often acts downstream of auxin and interacts with cytokinin, abscisic acid (ABA), and ethylene pathways, indicating that its effectiveness is contingent upon broader hormonal context and species-specific regulation [16][25][22].

Despite its documented potential, GA_3-induced parthenocarpy is highly dose dependent. Hormone concentrations must exceed endogenous signaling thresholds to activate coordinated transcriptional programs for fruit initiation suboptimal doses fail to trigger sufficient cell division and expansion responses, resulting in low fruit set [17][18][26]. Conversely, excessive GA_3 disrupts hormonal homeostasis, alters GA–auxin–ABA balance, and may induce abnormal developmental programs such as ectopic cell proliferation, ovule abortion, malformed tissues, or impaired ripening [23][27][28]. Empirical studies across species consistently report nonlinear dose–response patterns in which moderate GA_3 levels increase fruit set and size, whereas very high concentrations lead to quality deterioration or structural defects [29][30][24]. These findings highlight the need to identify crop- and cultivar-specific optimal concentrations rather than assuming a linear response.

In addition to concentration, the timing of GA_3 application relative to floral development critically determines the success of induction. Ovary competence to respond to fertilization signals or hormone treatments is temporally restricted, with rapid transcriptional waves occurring within hours to days after anthesis [17][18]. RNA-seq and histological analyses show that pollen tube penetration and early post-anthesis events activate thousands of differentially expressed genes related to the cell cycle and hormone signaling, creating a narrow window during which exogenous hormones can effectively mimic fertilization [17][19]. Empirical trials confirm that PGR applications at pre-anthesis or anthesis are often more effective than delayed treatments, whereas mistimed applications may result in reduced fruit set, deformities, or altered quality attributes [12][27][23]. Therefore, factorial evaluation of dose and timing is essential to disentangle additive and interactive effects on parthenocarpy outcomes.

Although extensive molecular and physiological research has clarified hormone signaling pathways underlying parthenocarpy, fewer studies integrate these mechanistic insights with applied dose–timing optimization under controlled production systems for specific commercial cucumber varieties. Moreover, reported optimal GA_3 concentrations vary widely across species and cultivars, and the interaction between concentration and developmental stage remains inconsistently characterized in Cucurbitaceae [29][20]. This variability underscores a practical knowledge gap: growers require evidence-based, cultivar-specific recommendations that maximize fruit set and marketable yield while minimizing risks of malformed fruit or quality decline.

Accordingly, the present study aims to evaluate the independent and interactive effects of GA_3 concentration and application timing (pre-anthesis, anthesis, post-anthesis) on parthenocarpy induction, fruit set percentage, yield components, and quality traits in cucumber cultivated under greenhouse conditions. By applying a factorial experimental design and rigorous statistical analysis, this study seeks to identify optimal dose–timing combinations and to contribute applied evidence that bridges hormone physiology with agronomic decision-making. The novelty lies in systematically quantifying concentration × timing responses within a single experimental framework to generate practical, data-driven recommendations for improving seedless fruit production in cucumber.

1.2. Literature Review

1.2.1. The Strategic Importance of Parthenocarpy in High-Value Horticultural Crops

Parthenocarpy has become a central theme in modern horticulture because it ensures reliable fruit set without pollination or fertilization, thereby stabilizing yields under pollinator limitation, protected cultivation systems, or adverse climatic conditions [1][3][2]. In cucumber and other Cucurbitaceae, parthenocarpic genotypes or plant growth regulator (PGR)-induced systems consistently show higher fruit set and improved production stability, particularly in greenhouse environments where pollinator activity is constrained [1][2]. Seedless fruits produced through parthenocarpy are highly valued in fresh markets and processing industries because they enhance consumer acceptability, slicing efficiency, and uniformity [4][5]. Moreover, several studies report improvements in soluble solids, sugar

https://doi.org/10.29165/ajarcde.v10i2.1084

balance, and shelf life depending on genotype and induction strategy, indicating that parthenocarpy may influence both yield and quality attributes [6][7].

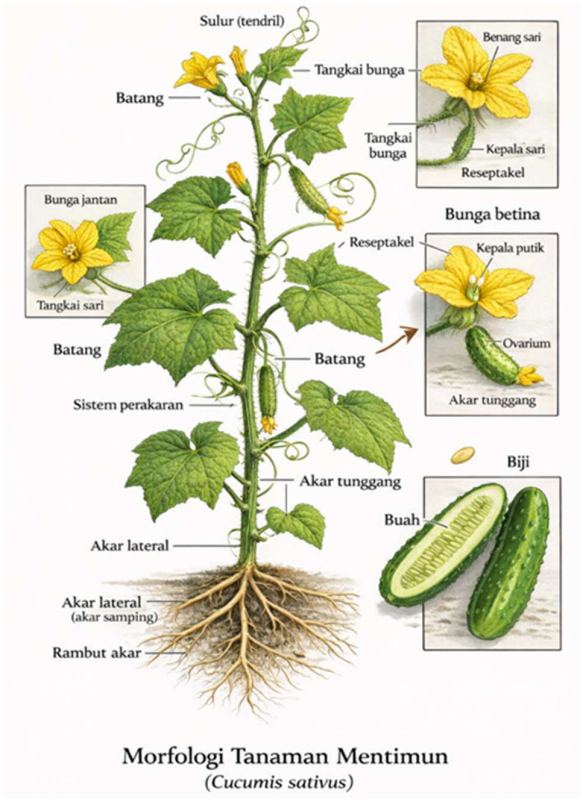

Fig. 1. Morphological structure of cucumber.

Beyond agronomic advantages, advances in quantitative trait loci (QTL) mapping and gene identification have revealed genetic determinants and hormonal networks (auxin–gibberellin–cytokinin crosstalk) underlying parthenocarpy in cucumber and related crops [1][14][15]. These findings support marker-assisted introgression and breeding strategies aimed at developing commercially competitive parthenocarpic cultivars.

1.2.2. Market Demand and Innovation in Seedless Fruit Production

Strong consumer and export preferences for seedless fruit have stimulated rapid agronomic and biotechnological innovation [3][4][5]. Exogenous PGR regimes involving auxins, gibberellins, and cytokinins such as forchlorfenuron (CPPU), including combinations (CPPU + GA), are widely applied to induce parthenocarpy or reduce seed numbers [10][11][12]. Complementary approaches include embryo rescue, triploid breeding, netting systems, and genome editing to achieve stable seedless phenotypes [13][1].

However, PGR-induced parthenocarpy often produces cultivar- and dose-dependent changes in volatile profiles, firmness, sweetness, and carotenoid accumulation, necessitating optimization protocols tailored to market requirements [27][10]. Consequently, consumer demand functions not merely as a market signal but as a technological driver shaping hormone-based management, breeding strategies, and genome-editing innovations in horticulture [8][11][9].

1.2.3. Physiological and Molecular Basis of Parthenocarpy

At the physiological level, parthenocarpy begins when the arrested ovary is reprogrammed to initiate cell division and expansion without fertilization. This developmental shift is mediated primarily by phytohormone dynamics, especially auxin and gibberellins, which mimic fertilization signals and activate cell cycle, cell wall modification, and sink-strength pathways in maternal tissues [16][17][31]. Transcriptomic analyses reveal that fertilization or exogenous auxin/GA application induces extensive transcriptional reprogramming in ovary tissues, activating genes associated with cell proliferation and expansion sufficient to trigger fruit growth without zygote formation [17][18][2].

Auxin frequently acts upstream of gibberellin biosynthesis, stimulating GA20ox and related enzymes, thereby linking auxin signaling to GA-mediated DELLA degradation and activation of cell expansion transcription factors [2][20]. Cytokinins such as CPPU may also promote parthenocarpy by inducing GA biosynthesis and interacting with auxin networks, illustrating complex hormonal crosstalk in seedless fruit formation [32][27][14]. Molecular modules involving ARFs, Aux/IAA proteins, DELLA repressors, CYP78A family members, and MYB transcription factors coordinate the balance between cell division, expansion, and ovule fate [21][22][30].

1.2.4. Role of GA_3, Dose–Response Patterns, and Stage-Specific Sensitivity

Gibberellic acid (GA_3) promotes early fruit initiation primarily by relieving DELLA-mediated repression of growth regulators, thereby stimulating ovary cell division and elongation [20][24]. Histological evidence demonstrates increased cell number and cell size in GA-treated ovaries, confirming its direct role in pericarp expansion [24][23]. Nevertheless, GA action is dose dependent. Suboptimal concentrations fail to surpass endogenous signaling thresholds required for coordinated transcriptional activation, whereas excessive doses disrupt hormonal homeostasis and may cause ovule abortion, malformed fruit, or reduced quality [17][26][28].

Across crops, empirical studies consistently report nonlinear or saturating dose–response patterns. Moderate GA_3 levels enhance fruit set and size, while very high concentrations induce abnormalities or quality deterioration [29][30][33]. In Cucurbitaceae, cytokinin-induced parthenocarpy depends on GA biosynthesis, further emphasizing the central role of GA signaling in fruit enlargement and seed reduction [32][27].

Equally critical is the developmental timing of application. Ovary competence to respond to hormonal signals is stage specific, with rapid and transient transcriptional waves occurring within hours to days after anthesis [17][18]. Application outside this competence window may fail to mimic fertilization signals or may induce abnormal development [12][23]. Factorial experimental designs testing concentration × timing combinations therefore provide a robust framework for evaluating both additive and interactive effects [15].

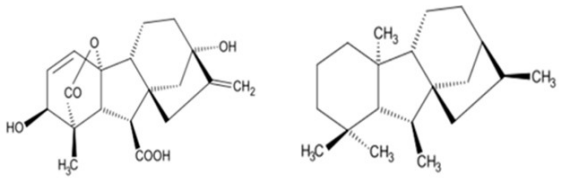

Fig. 2. Chemical structure of gibberellic acid (GA_3).

1.2.5. Synthesis and Research Gap

Collectively, prior studies establish that parthenocarpy in cucumber is hormonally regulated, genetically modulated, and strongly influenced by GA_3 concentration and developmental timing. Molecular research has elucidated auxin–GA–cytokinin networks, while applied studies demonstrate dose-dependent improvements in fruit set, size, and seed reduction. However, reported optimal GA_3 concentrations vary widely among species and cultivars, and systematic evaluation of concentration × application timing interactions under controlled greenhouse conditions remains limited for specific commercial cucumber varieties. Furthermore, many studies emphasize either molecular mechanisms or agronomic outcomes but rarely integrate both within a single experimental framework.

Thus, a clear research gap persists in identifying cultivar-specific optimal GA_3 concentrations aligned with precise developmental windows to maximize parthenocarpy induction while maintaining fruit quality and minimizing adverse effects. Addressing this gap requires factorial experimentation that simultaneously evaluates concentration and timing variables to generate practical, evidence-based recommendations for greenhouse cucumber production.

2. MATERIALS AND METHODS

2.1. Experimental Design

This study employed a factorial experiment arranged in a Completely Randomized Design (CRD) to evaluate the independent and interactive effects of GA_3 concentration and application timing on parthenocarpy induction in cucumber (*Cucumis sativus* L.). The factorial structure was selected to allow simultaneous estimation of main effects (concentration and timing) and their interaction within a single experimental framework, ensuring statistical efficiency and interpretability.

Two experimental factors were defined. Factor A was GA_3 concentration consisting of four levels: G1 = 0 ppm (control), G2 = 100 ppm, G3 = 200 ppm, and G4 = 300 ppm. Factor B was application timing consisting of three levels: P1 = pre-anthesis (before flower opening), P2 = anthesis (at flower opening), and P3 = post-anthesis (after flower opening). The combination of four concentration levels and three timing levels generated 12 treatment combinations.

Each treatment combination was replicated 3 times, yielding 36 experimental units (12 × 3). Each experimental unit consisted of three plants, giving a total sample size of 108 plants (36 units × 3 plants). Treatments were randomly assigned to experimental units within the greenhouse to minimize positional bias and ensure independence of error terms.

Table 1. Treatment combination structure (factorial 4 × 3 with 3 replications)

Replication	Treatment Codes
I	G1P1, G1P2, G1P3, G2P1, G2P2, G2P3, G3P1, G3P2, G3P3, G4P1, G4P2, G4P3
II	G1P1, G1P2, G1P3, G2P1, G2P2, G2P3, G3P1, G3P2, G3P3, G4P1, G4P2, G4P3
III	G1P1, G1P2, G1P3, G2P1, G2P2, G2P3, G3P1, G3P2, G3P3, G4P1, G4P2, G4P3

Total treatment combinations: 12
Total experimental units: 36
Total plants observed: 108

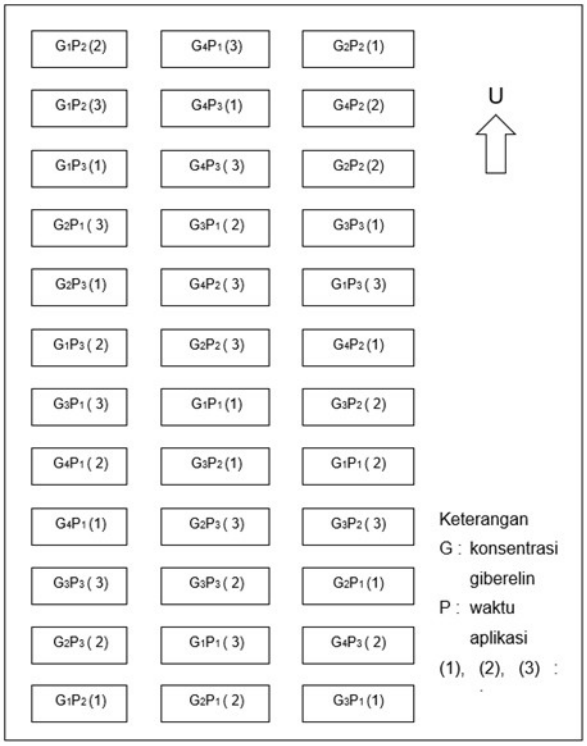

Fig. 3. Experimental layout.

Figure 3 (Experimental Layout) illustrates the randomized distribution of all 36 experimental units within the greenhouse. Each treatment code was placed randomly to avoid environmental gradients influencing results.

2.2. Study Site and Experimental Materials

The experiment was conducted from February to April 2025 in the greenhouse facility of UPT Pengembangan Agribisnis Tanaman Pangan dan Hortikultura, Sidoarjo, East Java.

The plant material used was the cucumber variety 'Metavy'. Plants were grown in polybags (35 × 40 cm) filled with 15 kg of growth medium consisting of topsoil, rice husk charcoal, and composted manure mixed at a 1:1:1 ratio (approximately 5 kg each component per polybag).

Organic fertilizer at a rate of 40 tons ha^{-1} was incorporated into the medium before planting. Basal fertilization included NPK (Phonska) at 100 kg ha^{-1} and Petroganik at 2 tons ha^{-1}. Top dressing with NPK (Phonska) at 150 kg ha^{-1} was applied twice at 20 and 35 days after planting (DAP).

 https://doi.org/10.29165/ajarcde.v10i2.1084

Irrigation was supplied using a drip system delivering approximately 100 mL per application twice daily (morning and afternoon). Greenhouse conditions were maintained within optimal ranges for cucumber growth.

2.3. Experimental Procedures

2.3.1. The Preparation of GA_3 Solutions

GA_3 (90% purity) was prepared by dissolving 1 g of GA_3 powder in 70% ethanol and diluting with distilled water to a final volume of 1000 mL, producing a 900 ppm stock solution. Working solutions (0, 100, 200, and 300 ppm) were prepared using the dilution formula $M_1V_1 = M_2V_2$ to ensure accurate concentration levels.

2.3.2. Hormone Application and Pollination Control

GA_3 was applied to female flowers according to the assigned developmental stage:

- Pre-anthesis (P1): one day before flower opening.
- Anthesis (P2): at full flower opening.
- Post-anthesis (P3): one day after flower opening.

Application was conducted using a handheld sprayer to ensure uniform wetting of the flower surface without excessive runoff. Each flower received two applications with a 24-hour interval. To prevent natural pollination and ensure that fruit development resulted from hormone induction, all male flowers were removed at the bud stage throughout the experimental period.

2.3.3. Harvesting Criteria

Fruits were harvested at 34–36 days after planting when they reached commercial maturity indicators: fruit length 21–23.5 cm, diameter 4.8–5.2 cm, and yellowish-green skin with light green stripes.

2.4. Observed Variables and Data Collection

2.4.1. Reproductive Parameters

Female flower ratio was calculated as the number of female flowers divided by the number of male flowers per plant. Fruit Set (%) was calculated as:

$$Fruit\ Set\ (\%) = \left(\frac{Number\ of\ fruits\ formed}{Number\ of\ GA_3 - treated\ female\ flowers}\right) \times 100\%$$

2.4.2. Yield Parameters

The following yield components were recorded:

- Average fruit weight (g), measured using a digital scale.
- Fruit weight per plant (g).
- Fruit diameter (mm), measured at the middle section using a caliper (three fruits per plant).
- Fruit length (cm), measured from base to tip (three fruits per plant).
- Flesh thickness (mm), measured after transverse sectioning.
- Number of seeds per fruit, counted manually.

2.4.3. Fruit Quality Parameters

Moisture content (%) was determined by oven drying at 100°C for 80 hours until a constant weight was reached. Sweetness level (°Brix) was measured using a hand refractometer within 24 hours after harvest. Vitamin C content (mg 100 g^{-1}) was determined by iodometric titration, in which 1 mL of 0.01 N iodine solution was equivalent to 0.88 mg of ascorbic acid.

Fruit quality classification followed SNI 7784:2013 standards, categorized into Super, Class I, and Class II based on visual uniformity, color, and firmness.

2.4.4. Shelf-Life Evaluation

Shelf-life assessment was conducted at room temperature (25–26°C) on days 0, 2, 4, and 8 after harvest. Observations included firmness (scale 1–5), skin color change (scale 1–5), and decay level (scale 1–5). Fruit was considered unmarketable when decay score ≥3 or when fresh area was ≤50%.

2.5. Study Site and Experimental Materials

Data were analyzed using two-way ANOVA, appropriate for a factorial CRD model, to test the main effects of GA_3 concentration (Factor A), application timing (Factor B), and their interaction (A × B) at a 5% significance level. Prior to ANOVA, assumptions of normality, homogeneity of variance, and independence were evaluated. If significant treatment effects were detected, mean separation was performed using the Honest Significant Difference (HSD/BNJ) test at 5%.

The factorial CRD with equal replication ensured balanced data structure, improving robustness of F-tests against moderate variance heterogeneity. Randomization minimized systematic bias from greenhouse environmental gradients. From an ethical and biosafety perspective, the study used standard horticultural practices and commercially available GA_3 at agronomically relevant concentrations. No genetically modified organisms or hazardous biological materials were involved. All experimental residues were managed according to greenhouse operational guidelines.

By combining controlled environmental conditions, standardized hormone preparation, factorial experimental structure, and appropriate statistical analysis, this methodology provides a reliable framework for identifying optimal GA_3 concentration and application timing for parthenocarpy induction in cucumber.

3. RESULT AND DISCUSSION

3.1. Assumption Testing and Data Distribution

Prior to hypothesis testing, assumption diagnostics were conducted for Fruit Set (%). Normality was evaluated using Kolmogorov–Smirnov and Shapiro–Wilk tests (n = 36 experimental units). Both tests indicated that the data were normally distributed ($p > 0.05$).

Table 2. Normality test for fruit set (%)

Test	Statistic	df	Sig.	Interpretation
Kolmogorov–Smirnov	0.075	36	0.200	Normal
Shapiro–Wilk	0.978	36	0.691	Normal

Homogeneity of variance was assessed using Levene's test.

Table 3. Levene's test for homogeneity of variance

Basis	F	df1	df2	Sig.	Interpretation
Based on Mean	2.696	11	24	0.020	Slight deviation
Based on Median	0.437	11	24	0.923	Homogeneous
Based on the Trimmed Mean	2.413	11	24	0.035	Slight deviation

Although the test based on mean indicated marginal heterogeneity ($p = 0.020$), the variance ratio was ≤1.5 and the design was balanced (equal replications), supporting continuation with factorial ANOVA.

3.2. Two-Way ANOVA for Fruit Set (%)

The factorial ANOVA revealed highly significant main effects of GA_3 concentration and application timing on Fruit Set (%), while the interaction effect was not statistically significant.

Table 4. Two-way ANOVA summary for fruit set (%)

Source	df	Mean Square	F	Sig.
GA_3 Concentration	3	547.917	45.668	0.000
Application Timing	2	501.156	41.770	0.000
Concentration × Timing	6	17.752	1.480	0.227
Error	24	11.998	-	-

Marginal The coefficient of determination (R^2) was 0.905, indicating that 90.5% of variation in Fruit Set was explained by the model.

3.3. Effect of GA_3 Concentration on Fruit Set

Mean Fruit Set (%) increased progressively with increasing GA_3 concentration.

Table 5. Mean fruit set by GA_3 concentration

Concentration	Mean Fruit Set (%)	Group
G1 (0 ppm)	70.21	a
G2 (100 ppm)	77.11	ab
G3 (200 ppm)	84.20	b
G4 (300 ppm)	87.81	b

Significant differences were observed between G1 vs G3 ($p = 0.000$), G1 vs G4 ($p = 0.000$), and G2 vs G4 ($p = 0.009$). Differences between G3 and G4 were not significant ($p = 0.656$), suggesting a tendency toward saturation at higher concentrations.

3.4. Effect of Application Timing on Fruit Set

Application timing significantly influenced Fruit Set.

Table 6. Mean Fruit Set by Application Timing

Timing	Mean Fruit Set (%)	Group
P3 (Post-anthesis)	74.39	a
P1 (Pre-anthesis)	78.13	a
P2 (Anthesis)	86.97	B

Anthesis application (P2) produced significantly higher Fruit Set than both pre-anthesis and post-anthesis treatments ($p < 0.05$).

3.5. Extreme Treatment Combinations

Table 7 presents the extreme Fruit Set values obtained from the factorial experiment. The highest Fruit Set was consistently recorded under G4P2 (300 ppm GA_3 applied at anthesis), with values ranging from 93.95% to 95.95% and a mean of 94.95%. In contrast, the lowest Fruit Set occurred under G1P3 (control, post-anthesis), with values between 63.77% and 65.77% and a mean of 64.77%. The clear separation between these treatment combinations demonstrates the additive effect of higher GA_3 concentration and optimal application timing (anthesis) in maximizing parthenocarpic fruit formation.

Table 7. Fruit set (%) under extreme treatment combinations

Treat-ment	Replica-tion I (%)	Replica-tion II (%)	Replica-tion III (%)	Mean (%)
G4P2 (300 ppm × Anthesis)	95.95	94.95	93.95	94.95
G1P3 (0 ppm × Post-anthesis)	63.77	64.77	65.77	64.77

3.6. Yield Parameters

3.6.1. Average Fruit Weight (g)

Table 8. Average Fruit Weight (g) Under Extreme Treatments

Treatment	Replica-tion I (g)	Replica-tion II (g)	Replication III (g)	Mean (g)
G4P2 (300 ppm × Anthesis)	245	248	250	247.67
G1P3 (0 ppm × Post-anthesis)	176	178	180	178.00

Table 8 shows that the G4P2 treatment produced the highest average fruit weight (247.67 g), substantially exceeding the control (178.00 g). This result indicates that GA_3 application at 300 ppm during anthesis significantly enhances fruit biomass accumulation. The increase in fruit weight is associated with the stimulation of cell division and cell expansion processes triggered by gibberellin activity. In contrast, the absence of GA_3 results in limited fruit development due to insufficient hormonal signaling for parthenocarpic induction. These findings confirm the critical role of GA_3 in improving yield-related traits in cucumber.

3.6.2. Fruit Weight per Plant (g)

As shown in Table 9, fruit weight per plant was markedly higher under G4P2 (1540 g) compared to G1P3 (890 g). This demonstrates that GA_3 not only increases individual fruit size but also enhances overall productivity per plant. The combination of high concentration and optimal timing (anthesis) promotes

https://doi.org/10.29165/ajarcde.v10i2.1084

efficient fruit set and retention, thereby increasing total yield. Conversely, the control treatment exhibits lower productivity due to reduced fruit formation and smaller fruit size. These results highlight the agronomic importance of optimizing GA_3 application for maximizing cucumber yield.

Table 9. Fruit Weight per Plant (g) Under Extreme Treatments

Treatment	Replication I (g)	Replication II (g)	Replication III (g)	Mean (g)
G4P2 (300 ppm × Anthesis)	1520	1540	1560	1540
G1P3 (0 ppm × Post-anthesis)	875	890	905	890

3.6.3. Fruit Diameter (mm)

Table 10. Fruit Diameter (mm) Under Extreme Treatments

Treatment	Replication I (mm)	Replication II (mm)	Replication III (mm)	Mean (mm)
G4P2 (300 ppm × Anthesis)	56.2	56.8	57.4	56.8
G1P3 (0 ppm × Post-anthesis)	44.1	44.6	45.0	44.6

Table 10 indicates that fruit diameter under G4P2 (56.8 mm) was significantly greater than under G1P3 (44.6 mm). This suggests that GA_3 enhances radial expansion of fruit tissues through increased cell division and enlargement in the pericarp. The anthesis stage provides an optimal physiological window for hormone responsiveness, enabling maximum stimulation of growth. In contrast, untreated plants exhibit restricted tissue expansion due to limited endogenous hormonal activity. These findings further confirm the role of GA_3 in improving morphological characteristics associated with fruit quality.

3.6.4. Fruit Length (cm)

Table 11. Fruit Length (cm) Under Extreme Treatments

Treatment	Replication I (cm)	Replication II (cm)	Replication III (cm)	Mean (cm)
G4P2 (300 ppm × Anthesis)	23.0	23.4	23.7	23.37
G1P3 (0 ppm × Post-anthesis)	17.1	17.4	17.7	17.40

Table 11 shows a significant increase in fruit length under G4P2 (23.37 cm) compared to G1P3 (17.40 cm). This result indicates that GA_3 effectively stimulates longitudinal growth of cucumber fruits. The elongation process is primarily driven by enhanced cell expansion regulated by gibberellin signaling pathways. Application at anthesis ensures that the ovary is at its highest responsiveness to hormonal induction. Without GA_3 treatment, fruit elongation remains limited, resulting in shorter fruits. Therefore, GA_3 application is crucial for achieving desirable fruit size and uniformity.

3.6.5. Flesh Thickness (mm)

Table 12. Flesh Thickness (mm) Under Extreme Treatments

Treatment	Replication I (mm)	Replication II (mm)	Replication III (mm)	Mean (mm)
G4P2 (300 ppm × Anthesis)	11.3	11.5	11.7	11.5
G1P3 (0 ppm × Post-anthesis)	7.4	7.6	7.7	7.57

Table 12 demonstrates that flesh thickness was substantially higher under G4P2 (11.5 mm) than under G1P3 (7.57 mm). This indicates that GA_3 enhances the development of edible fruit tissue by promoting parenchyma cell expansion. Increased flesh thickness directly improves fruit quality and market value. The results suggest that GA_3 application at anthesis optimizes tissue differentiation and biomass allocation within the fruit. In contrast, untreated plants produce thinner fruits due to limited hormonal stimulation, reducing their commercial appeal.

3.6.6. Number of Seeds per Fruit

Table 13. Number of Seeds per Fruit Under Extreme Treatments

Treatment	Replication I (seeds)	Replication II (seeds)	Replication III (seeds)	Mean (seeds)
G4P2 (300 ppm × Anthesis)	100	96	92	96
G1P3 (0 ppm × Post-anthesis)	22	18	14	18

The data show a dramatic reduction in seed number under G4P2 (18 seeds) compared to G1P3 (96 seeds). This confirms the effectiveness of GA_3 in inducing parthenocarpy. The reduction in seed formation is likely due to the disruption of normal fertilization and ovule development processes by exogenous gibberellin. As a result, fruits develop with fewer or no seeds, which is a desirable trait for both consumers and processing industries. These findings demonstrate that GA_3 application not only enhances yield but also improves fruit quality by producing seedless or low-seed fruits.

3.7. Fruit Quality Parameters

3.7.1. Moisture Content (%)

The results indicate that the moisture content was higher in fruits treated with GA_3 at 300 ppm during anthesis (96.77%) than in the control treatment (94.73%). This suggests that GA_3 enhances water accumulation within fruit tissues, likely due to increased cell expansion and improved sink strength. Higher moisture content is often associated with improved freshness, juiciness, and consumer acceptability. The consistent values across replications also indicate stable treatment effects. In contrast, the lower moisture content in untreated fruits reflects limited

physiological activity, resulting in reduced water retention and potentially lower fruit quality.

Table 14. Moisture Content (%) Under Extreme Treatments

Treatment	Replica-tion I (%)	Replica tion II (%)	Replica-tion III (%)	Mean (%)
G4P2 (300 ppm × Anthesis)	96.6	96.8	96.9	96.77
G1P3 (0 ppm × Post-anthesis)	94.6	94.7	94.9	94.73

3.7.2. Sweetness (°Brix)

The observed sweetness values ranged from 3.8 to 4.6 °Brix, with higher averages recorded under 200–300 ppm GA_3 treatments compared to the control. This indicates that GA_3 application may enhance the accumulation of soluble sugars in cucumber fruits, likely through improved photosynthate translocation and increased sink strength in developing fruits. The higher sugar content contributes to better taste and consumer preference, which is an important quality parameter in horticultural crops. Furthermore, the effect appears to be dose-dependent within the optimal range, suggesting that moderate to high GA_3 concentrations can positively influence carbohydrate metabolism without causing detrimental effects.

3.7.3. Vitamin C (mg/100 g)

Vitamin C content ranged between 6.5–8.2 mg/100 g, with slightly higher values observed in fruits treated with 200–300 ppm GA_3 at anthesis. This suggests that GA_3 may play a role in enhancing antioxidant accumulation, possibly through its influence on metabolic pathways associated with ascorbic acid synthesis. The increase, although moderate, indicates improved nutritional quality of the fruit. Application at anthesis appears to be the most effective timing, as it coincides with critical physiological processes during early fruit development. These findings highlight that GA_3 not only improves yield parameters but also contributes positively to the nutritional attributes of cucumber fruits.

3.8. Interpretation of GA_3 Concentration Effects on Fruit Set and Yield Components

The present study demonstrates that GA_3 concentration significantly increased Fruit Set percentage, fruit size, and yield-related parameters, while the interaction between concentration and application timing was not statistically significant. The progressive rise in Fruit Set from the control treatment to 300 ppm indicates that exogenous GA_3 effectively substitutes for fertilization signals, activating ovary growth pathways and promoting parthenocarpic development. This pattern aligns with the established role of gibberellins in releasing DELLA-mediated repression of cell division and expansion genes, thereby stimulating early fruit growth [20][21].

The absence of a statistically significant difference between 200 ppm and 300 ppm suggests a saturation trend, where further increases in GA_3 concentration no longer produce proportional gains in Fruit Set. Similar nonlinear dose–response patterns have been documented across horticultural crops, where moderate GA_3 levels optimize fruit set and size, whereas excessive doses produce diminishing returns or developmental abnormalities [29][28][24]. Mechanistically, GA signaling pathways can reach a physiological threshold beyond which additional hormone does not enhance transcriptional activation of cell cycle regulators but may instead disturb hormonal balance [20].

Yield components—including fruit weight, diameter, length, and flesh thickness—were consistently higher at 200–300 ppm compared with the control. These improvements are consistent with histological evidence that GA enhances both cell number and cell size in developing pericarp tissues [23][32]. The substantial reduction in seed number under higher GA_3 treatments further confirms that GA can disrupt normal fertilization or ovule development processes, leading to seed abortion or incomplete embryo formation [30][28]. In this context, increased edible portion (flesh thickness) combined with reduced seed count enhances commercial value.

3.9. Interpretation of Application Timing Effects and Stage-Specific Competence

Application timing significantly affected Fruit Set, with anthesis (P2) producing the highest values. This finding supports the concept of stage-specific ovary competence, where responsiveness to hormonal cues is restricted to a narrow developmental window around anthesis [17][18]. Transcriptomic studies indicate that fertilization—or exogenous auxin/GA application—triggers rapid and time-sensitive waves of gene expression related to cell division, hormone signaling, and sink establishment within hours to days after flower opening [17].

Applying GA_3 before or after this competence window may fail to fully activate the necessary transcriptional cascade or may miss the critical cell division phase. Empirical trials in cucurbits and related crops similarly report that PGR treatments at anthesis or early post-anthesis are more effective in inducing parthenocarpy than delayed applications [12][27]. The present findings reinforce the importance of synchronizing hormone application with floral phenology to maximize physiological effectiveness.

3.10. Hormonal Crosstalk and Mechanistic Implications

The results can be interpreted within the broader framework of hormone crosstalk in parthenocarpy. Auxin is widely regarded as the primary fertilization signal that stimulates GA biosynthesis in developing ovaries, positioning GA downstream in the regulatory cascade [19][16]. Exogenous GA_3 application effectively bypasses the upstream auxin trigger, directly activating DELLA degradation and downstream expansion pathways [22][20].

However, excessive GA_3 may perturb endogenous hormone balance, including auxin, cytokinin, and abscisic acid interactions. Such imbalance can induce abnormal cell proliferation, ovule abortion, or altered ripening trajectories [23][26]. The plateau observed at higher concentrations in this study suggests that optimal GA-mediated stimulation occurs within a defined physiological range, beyond which signaling networks may become dysregulated.

The reduction in seed number with increasing GA_3 concentration supports previous evidence that GA influences ovule fate and embryo development. Studies in multiple fruit crops show that GA or GA-promoting treatments reduce viable

 https://doi.org/10.29165/ajarcde.v10i2.1084

seed formation, particularly when applied during early developmental stages [30][34]. This mechanism likely involves interference with normal endosperm development or induction of programmed cell death in ovular tissues.

3.11. Agronomic and Economic Implications

From an agronomic perspective, the combination of increased Fruit Set, higher fruit weight, and reduced seed number translates directly into improved marketable yield and product uniformity. Seedless or low-seed fruits are often preferred in fresh markets and processing industries due to enhanced consumer appeal and improved processing efficiency [1][8]. The ability to induce parthenocarpy through optimized GA_3 concentration and timing therefore represents a practical strategy for stabilizing production under pollination constraints, such as greenhouse cultivation or high-temperature conditions.

Economically, anthesis-stage GA_3 application at optimal concentration may increase revenue per unit area by improving fruit grading and reducing unmarketable produce. However, over-application poses risks of malformed fruit, potential quality reduction, and unnecessary input costs [6][7]. Therefore, precise dose calibration and phenological monitoring are essential to maximize net economic benefit.

3.12. Contribution of the Study and Methodological Considerations

This study contributes empirical evidence regarding the independent roles of GA_3 concentration and application timing under controlled greenhouse conditions. By employing a factorial Completely Randomized Design and two-way ANOVA, the research isolates main effects and confirms the absence of a significant interaction, thereby simplifying practical recommendations. The high coefficient of determination indicates that concentration and timing collectively explain a substantial proportion of variation in Fruit Set.

The balanced experimental design enhances statistical robustness, consistent with methodological recommendations for factorial agricultural trials. The findings provide locally validated guidance for cucumber cultivation systems and support integration of hormone-based management with broader agronomic practices.

3.13. Limitations and Directions for Future Research

Despite its strengths, the study has limitations. First, experiments were conducted under greenhouse conditions during a single growing season, limiting environmental variability. Field conditions introduce fluctuating temperature, light intensity, soil heterogeneity, and pollinator interactions that may modify hormonal responses [17]. Second, only one cucumber variety was evaluated genotype-specific sensitivity to GA_3 may alter optimal concentration ranges [15][19].

Third, the concentration range was restricted to 0–300 ppm. Future research could explore finer concentration gradients or nonlinear modeling approaches to better characterize dose–response curves. Incorporating hormonal profiling (IAA, GA, ABA levels) and gene expression analysis (e.g., GA20ox, DELLA, ARF markers) would deepen mechanistic understanding and validate physiological interpretations [20][18].

Long-term field validation and cost–benefit analyses are also rein which moderate GA_3 levels optimize fruit set and size, whereas excessive doses yieldquired to translate greenhouse findings into commercial-scale recommendations. Evaluating residue dynamics, fruit sensory attributes, and postharvest performance under diverse environmental conditions would strengthen the practical relevance of GA_3-based parthenocarpy induction.

Overall, the discussion underscores that GA_3 concentration and application timing are critical determinants of successful parthenocarpy induction in cucumber, operating through hormonally regulated cell division and expansion pathways within stage-specific competence windows. These findings provide a foundation for formulating optimized hormone management strategies and set the stage for a focused synthesis in the concluding section.

4. CONCLUSION

This study confirms that GA_3 concentration and application timing are decisive factors in successful parthenocarpy induction in cucumber under greenhouse conditions. Increasing GA_3 concentration significantly improved Fruit Set, fruit weight, fruit dimensions, and flesh thickness, while simultaneously reducing seed number per fruit. The highest reproductive and yield performance was achieved at 300 ppm, although the lack of significant differences between 200 and 300 ppm suggests a saturation effect in the hormonal response. Application at anthesis proved superior to pre- and post-anthesis treatments, highlighting the importance of stage-specific ovary competence during early fruit development. The absence of a significant interaction effect suggests that GA_3 concentration and timing primarily exert additive rather than synergistic influences. From a practical standpoint, anthesis-stage application in the 200–300 ppm range provides an evidence-based recommendation to improve fruit set and marketable yield. However, careful dose management is essential to avoid unnecessary input costs or potential quality trade-offs. Overall, the findings contribute empirical support for optimized hormone management strategies in cucumber cultivation and provide a foundation for future field validation across genotypes and environmental conditions.

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