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Research Article
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Enhancing growth, yield, and fruit quality of Kulai chilli (*Capsicum annuum* L.) using selected plant growth regulators

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Abstract: Plant growth regulators (PGRs) offer a potential means of improving chilli productivity by regulating vegetative growth, flowering, fruit development, and biochemical quality. This study evaluated the responses of Kulai chilli (*Capsicum annuum* L.) to foliar applications of naphthaleneacetic acid (NAA; 20 and 40 mg L^{-1}), gibberellic acid (GA_3; 10 and 20 mg L^{-1}), and indole-3-acetic acid (IAA; 25 and 50 mg L^{-1}) under rain-shelter conditions in Sandakan, Sabah, Malaysia. The experiment was arranged in a completely randomised design comprising seven treatments, including a water-sprayed control, with five replications. Treatments were applied at 30 and 45 days after transplanting. Plant growth, flowering, fruit maturity, yield, fruit characteristics, capsaicin content, and vitamin C content were evaluated. GA_3 at 20 mg L^{-1} produced the tallest plants throughout the cultivation period, reaching 79.4 cm at 90 days after transplanting. IAA at 50 mg L^{-1} induced the earliest flowering and fruit maturity, reducing the time to the final maturity index from 50.4 days in the control to 41.8 days after anthesis. However, NAA at 40 mg L^{-1} produced the most favourable overall response, increasing cumulative yield per plant by 61.9% relative to the control and producing the greatest fruit weight and length. This treatment also resulted in the highest capsaicin and vitamin C contents. Seed number per fruit was not significantly affected by the treatments. These findings demonstrate that PGR responses are trait-specific: GA_3 primarily enhanced vegetative growth, IAA accelerated crop development, and NAA at 40 mg L^{-1} provided the best balance between earliness, yield, and fruit quality. Further multi-season and multi-location validation is required before commercial application.

Keywords: auxin; capsaicin; gibberellic acid; protected cultivation; vitamin C; yield

1. Introduction

Chilli (*Capsicum annuum* L.) is an economically important horticultural crop cultivated worldwide as a vegetable, spice, food ingredient, and source of health-promoting phytochemicals. Its fruits are valued for their colour, flavour, pungency, and nutritional composition, particularly their contents of vitamin C, carotenoids, phenolic compounds, and capsaicinoids. Capsaicin and dihydrocapsaicin are the principal compounds responsible for pungency and contribute to consumer preference, processing suitability, and market value, while vitamin C is an important antioxidant and indicator of fruit nutritional quality. The accumulation of these compounds is influenced by genotype, fruit developmental stage, and crop-management conditions (Zhang et al., 2022, 2023).

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Despite its commercial importance, chilli productivity is often constrained by excessive flower abscission, poor fruit set, fruit drop, irregular fruit development, and non-uniform maturity. These limitations may be intensified by unfavourable temperature, humidity fluctuations, nutrient imbalances, and other environmental stresses during flowering and early fruit development. Since final yield depends on successful flower retention, fruit initiation, assimilate allocation, and fruit growth, agronomic interventions that regulate these processes may improve production efficiency. The use of exogenous plant growth regulators (PGRs) has therefore received increasing attention as a strategy for enhancing the growth, yield, and quality of *Capsicum* crops (Ahmed et al., 2022; Moosavi et al., 2024).

Plant growth regulators are naturally occurring or synthetic organic compounds that modify plant physiological processes at relatively low concentrations. Their application may influence endogenous hormonal balance (Yirmibeş et al., 2025), cell division and elongation (Small and Degenhardt, 2018), nutrient translocation (Amanullah et al., 2010), assimilate partitioning, flowering, fruit initiation, abscission, and ripening (Bons and Kaur, 2019). However, plant responses depend on the type and concentration of the regulator, application timing, developmental stage, cultivar, and growing environment. Therefore, PGRs should be regarded as physiological signals whose effectiveness is determined by complex interactions among hormonal treatment, genotype, and environmental conditions (Lu et al., 2023; Moosavi et al., 2024).

Gibberellic acid (GA_3), indole-3-acetic acid (IAA), and naphthaleneacetic acid (NAA) are among the principal regulators associated with chilli growth and fruit development. GA_3 promotes cell division and elongation and is commonly associated with stem extension, leaf expansion, fruit enlargement, and increased vegetative vigour. Nevertheless, excessive vegetative stimulation may compete with reproductive growth, indicating that its concentration and application timing must be carefully optimised. IAA is a naturally occurring auxin that regulates cell enlargement, tissue differentiation, root and shoot development, flowering, and fruit initiation. NAA is a more physiologically stable synthetic auxin that has been used to improve flower retention, reduce abscission, stimulate fruit set, and support early fruit development (Maboko and Plooy, 2015; Xie et al., 2018; Singh et al, 2026).

Auxins and gibberellins also interact during reproductive development. In *C. annuum*, auxin-induced fruit set requires downstream gibberellin biosynthesis, indicating that auxins initiate fruit development while gibberellins subsequently support fruit growth (Tiwari et al., 2012). NAA may produce a stronger fruit-set response than IAA because of its greater physiological stability. Combined auxin and GA_3 treatments have also been reported to influence fruit weight, length, pericarp thickness, ripening, pigment accumulation, soluble solids, and vitamin C content in bell pepper, demonstrating that PGR responses involve coordinated hormonal interactions rather than the action of individual compounds alone (Moosavi et al., 2024).

Recent studies confirm the potential of PGRs to improve pepper productivity, although responses vary among cultivars. Ahmed et al. (2022) reported that foliar applications of GA_3 and NAA influenced flowering, fruit set, fruit number, yield, total soluble solids, vitamin C, and capsaicin content in hot pepper under protected cultivation. However, the magnitude of these responses differed among cultivars. Similarly, Lu et al. (2023) found that exogenous regulation of endogenous hormone levels increased pepper yield and enhanced soluble sugar, soluble protein, vitamin C, and capsaicin accumulation. These findings indicate that PGRs influence growth and quality through interconnected hormonal and metabolic pathways and that recommendations developed for one cultivar or production environment may not be directly transferable to another (Fenn and Giovannoni, 2021).

Fruit quality should be evaluated together with yield because increased fruit number or biomass does not necessarily result in improved nutritional or commercial value. Capsaicinoid

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accumulation varies among *Capsicum* genotypes and developmental stages because of differences in the regulation of capsaicin biosynthesis (Zhang et al., 2022). Vitamin C concentration is also influenced by fruit maturity and crop management, with contrasting responses reported between mature-green and red-ripe fruits (Zhang et al., 2023). PGRs may therefore influence fruit quality directly through hormonal regulation of metabolic pathways or indirectly through changes in fruit development, maturity, assimilate allocation, and nutrient distribution.

Although PGRs have been studied in several hot and sweet pepper cultivars, limited information is available on the comparative responses of Kulai chilli to NAA, GA_3, and IAA under the humid tropical and rain-shelter conditions of Sabah. Few studies have simultaneously evaluated vegetative growth, reproductive development, maturity, yield, capsaicin, and vitamin C. Cultivar-specific evaluation is therefore essential because genetic background may influence hormonal sensitivity, assimilate partitioning, fruit development, and biochemical composition.

Accordingly, this study aimed to evaluate the influence of NAA, GA_3, and IAA on the vegetative growth, reproductive development, maturity, yield attributes, capsaicin content, and vitamin C content of Kulai chilli grown under rain-shelter conditions at Universiti Malaysia Sabah, Sandakan. The study also sought to identify the treatment that produced the most favourable balance between plant growth, fruit yield, and biochemical quality.

2. Materials and Methods

2.1 Study site and crop establishment

The experiment was conducted from July to December 2024 under rain-shelter conditions at the Faculty of Sustainable Agriculture, Universiti Malaysia Sabah, Sandakan, Sabah, Malaysia (5.932311° N, 118.004213° E). Fruit-quality analyses were performed in the Postharvest Laboratory of the same faculty.

Seeds of Kulai chilli (*Capsicum annuum* L.) were obtained from the Malaysian Agricultural Research and Development Institute (MARDI). The seeds were soaked in water overnight, surface-dried, and sown individually in 104-cell germination trays containing cocopeat. Seedlings were irrigated twice daily, in the morning and afternoon. At 14 days after sowing, an AB nutrient solution with an electrical conductivity (EC) of approximately 1.5 dS m^{-1} was applied to support seedling development.

At 30 days after sowing, uniform and disease-free seedlings bearing six to eight fully expanded leaves were transplanted into 40.6 × 40.6 cm polyethylene bags filled to approximately three-quarters of their capacity with cocopeat. Seventy uniform plants were assigned to the experimental treatments, with one plant per bag. The bags were arranged at 60 × 60 cm spacing, and each plant was supplied through an individual fertigation dripper. Irrigation was applied five times daily.

The nutrient solution was prepared by diluting separate A and B fertiliser stock solutions in water. Its EC was adjusted according to crop age: 1.4–1.6 dS m^{-1} during weeks 1–2 after transplanting, 1.6–1.8 dS m^{-1} during week 3, 2.0–2.2 dS m^{-1} during week 4, 2.2–2.4 dS m^{-1} during week 5, 2.4–2.6 dS m^{-1} during weeks 6–7, and 2.5–2.6 dS m^{-1} during week 8. Weeds were removed manually at weekly intervals, and reflective silver mulch was placed around the planting bags to suppress weed growth.

2.2 Experimental design and plant growth regulator treatments

The experiment was arranged in a completely randomised design with seven treatments and 5 plants per treatment, giving a total of 35 experimental plants. The individual plant represented the experimental unit. The treatments are summarised as in Table 1.

Each PGR solution was prepared by dissolving the required mass of the respective compound in a minimal volume of alcohol and subsequently diluting the solution to 1 L with

distilled water. Accordingly, 20 or 40 mg NAA, 10 or 20 mg GA_3, and 25 or 50 mg IAA were used to prepare the respective treatment solutions. The PGR treatments were applied as foliar sprays at 30 and 45 days after transplanting (DAT). Each plant was sprayed using a knapsack sprayer until the foliage was uniformly wetted. Control plants were sprayed with distilled water following the same application schedule.

Table 1. Plant growth regulator treatments applied to Kulai chilli.

Treatment	Descriptions
C	Distilled-water control
NAA 20	Naphthaleneacetic acid at 20 mg L^{-1}
NAA 40	Naphthaleneacetic acid at 40 mg L^{-1}
GA_3 10	Gibberellic acid at 10 mg L^{-1}
GA_3 20	Gibberellic acid at 20 mg L^{-1}
IAA 25	Indole-3-acetic acid at 25 mg L^{-1}
IAA 50	Indole-3-acetic acid at 50 mg L^{-1}

2.3 Growth, phenology, yield, and fruit characteristics

Plant growth, phenological development, yield, and fruit characteristics were evaluated using plants from each treatment. Plant height was measured at 30, 60, and 90 days after transplanting (DAT) using a measuring tape. Measurements were taken from the surface of the growing medium to the terminal shoot apex and recorded in centimetres (cm).

Days to flowering were recorded as the number of days from transplanting until 50% of the monitored plants within a treatment had produced at least one fully opened flower. To evaluate fruit development and maturity, five flowers per monitored plant were randomly selected and tagged at anthesis. The number of days from anthesis to each of the five visually defined fruit-maturity indices (Table 2) was subsequently recorded and expressed as days after anthesis.

Fruit length, individual fruit fresh weight, and seed number were determined using 10 fruits at maturity index 2 collected from five plants in each treatment. Fruit length was measured from the pedicel end to the distal end using a digital calliper (DigiMaz, United Kingdom). Individual fruit fresh weight was measured using an electronic balance (OHAUS Corporation, USA), after which the fruits were opened and their seeds were counted. The mean fruit length, fresh weight, and seed number were calculated for each treatment.

Yield was evaluated using five plants per treatment. Fruits reaching maturity index 2 were harvested beginning approximately three months after transplanting. Subsequent harvests were conducted at two-week intervals until six months after transplanting, when fruit production began to decline. The fresh weights of fruits collected from successive harvests were summed to calculate cumulative yield per plant.

Table 2. Chilli fruit ripeness indices according to Noichinda et al. (2016).

Index	Descriptions
1	Immature fruit with a fully light green colour.
2	Slightly mature fruit with a dark green, glossy surface. Approximately 25% red colour.
3	Nearly mature fruit showing colour break with a mixture of green and red. Approximately 50% red colour.
4	Mature fruit with dark red colour covering most of the fruit surface. Approximately 75% red colour.
5	Fully mature fruit with 100% red colour.

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2.4 Vitamin C determination

Vitamin C was determined using the 2,6-dichlorophenolindophenol (DCPIP) titrimetric procedure described in AOAC Official Method 967.21, with modifications for chilli fruit extracts (AOAC International, 2019).

An ascorbic acid standard solution was prepared by dissolving 50 mg of analytical-grade ascorbic acid and diluting it to 50 mL with metaphosphoric acid-acetic acid solution. The dye solution was prepared by dissolving 42 mg sodium bicarbonate in approximately 50 mL deionised water, followed by the addition of 50 mg 2,6-dichlorophenolindophenol sodium salt. The solution was diluted to 200 mL with deionised water, filtered, transferred to an amber bottle, and stored under refrigeration.

The extraction solution was prepared by dissolving 7.5 g metaphosphoric acid in a mixture of 100 mL distilled water and 20 mL acetic acid. The solution was diluted to 250 mL with distilled water, filtered, and stored under refrigeration until analysis.

For each treatment, 100 g of randomly selected fruits at maturity index 2 were cut into small pieces and homogenised with 90 mL distilled water. The homogenate was filtered through a filter cloth, and the extract was analysed immediately to minimise oxidative loss of ascorbic acid.

The indophenol dye was standardised by titrating 2 mL of the ascorbic acid standard mixed with 5 mL metaphosphoric acid-acetic acid solution until a light but distinct rose-pink colour persisted for more than 5 s. A reagent blank was prepared and titrated using the same procedure. For sample determination, 2 mL chilli extract was mixed with 5 mL metaphosphoric acid-acetic acid solution and titrated to the same endpoint. Four technical titrations were performed for each sample. Vitamin C or ascorbic acid concentration was calculated using the equation below:

$$\text{Ascorbic acid concentration } \left(\text{mg L}^{-1}\right) = \frac{(\text{X} - \text{B}) \times \text{F} \times \text{V}}{\text{E} \times \text{Y}}$$

Where, X is the average volume (mL) of sample titration, B is the average volume (mL) of sample blank titration, F is the dye factor (mg of ascorbic acid mL^{-1} of indophenol dye), V is the volume of the initial sample extract (mL), E is the Volume of the extract aliquot taken for titration (mL), and Y is the volume of sample aliquot titrated.

2.5 Capsaicin determination

Capsaicin was determined using the spectrophotometric method described by Sadasivam and Manickam (1996), with minor modifications. Ten fruits from each treatment were oven-dried at 55 °C for four days and ground to a homogeneous powder. A 2-g portion of the ground sample was extracted in 100 mL ethanol for 24 h. Following extraction, 1 mL of the extract was diluted to 5 mL with ethanol. Immediately before spectrophotometric measurement, 0.5 mL of 0.5% vanadium oxychloride prepared in ethyl acetate was added to the diluted extract. The absorbance of the reagent blank, capsaicin standards, and samples was measured at 720 nm using a UV-visible spectrophotometer. A calibration curve was prepared using capsaicin standards ranging from 0.5 to 2.5 mg mL^{-1}. The capsaicin concentration of each sample was estimated from the linear relationship between standard concentration and absorbance.

2.6 Statistical analysis

Data were analysed according to a completely randomised design using one-way analysis of variance (ANOVA), with PGR treatment included as the fixed factor. Plant height data were analysed separately at 30, 60, and 90 DAT, while the number of days required to attain each fruit-maturity index was analysed separately for each maturity stage. When the treatment effect was significant, means were separated using Tukey's honestly significant difference test at ($p <$

0.05). Analyses were performed using IBM SPSS Statistics for Windows, version 17.0 (SPSS Inc., Chicago, IL, USA). The individual plant was considered the biological replicate for plant-level measurements. Technical laboratory replicates were averaged within each independent biological sample before statistical analysis.

3. Results and Discussion

3.1 Plant growth responses to plant growth regulators

Plant height increased progressively from 30 to 90 days after transplanting (DAT) across all treatments, but the magnitude of this increase differed among plant growth regulators (Table 3). GA_3 consistently produced the greatest vegetative response. At 30 DAT, plants treated with GA_3 at 20 mg L^{-1} reached 56.8 cm, representing a 32.7% increase over the untreated control. GA_3 at 10 mg L^{-1} also increased plant height to 51.1 cm. By 60 DAT, the two GA_3 treatments remained the tallest, with mean heights of 71.6 and 74.4 cm for GA_3 at 10 and 20 mg L^{-1}, respectively. At 90 DAT, GA_3 at 20 mg L^{-1} produced the greatest plant height of 79.4 cm, which was 14.1% greater than the control and significantly higher than both NAA treatments.

The sustained increase in plant height following GA_3 application is consistent with its established role in promoting internode extension through coordinated cell division and cell elongation. Gibberellins also influence source–sink relationships and the mobilisation of assimilates towards actively growing tissues. Recent work in bell pepper has similarly demonstrated that exogenous phytohormones significantly alter morphological traits, including fruit length, plant development, and biomass allocation (Fenn and Giovannoni, 2021; Moosavi et al., 2024). However, the present results also show that increased plant height did not necessarily translate into the greatest yield, indicating that vegetative vigour alone is not a reliable predictor of reproductive productivity.

NAA produced comparatively smaller plants, particularly at 20 mg L^{-1}, which recorded the lowest mean height at all three sampling dates. At 90 DAT, plants treated with NAA at 20 and 40 mg L^{-1} reached 62.1 and 65.8 cm, respectively, compared with 69.6 cm in the control. Nevertheless, the lower stature of NAA-treated plants was not associated with reduced yield. Instead, NAA at 40 mg L^{-1} produced the highest yield and fruit-quality values, suggesting that this treatment favoured reproductive sink development rather than excessive stem elongation. This distinction is agronomically important because an effective PGR treatment should improve productive growth rather than simply increase vegetative size.

Table 3. Plant height of Kulai chilli treated with different concentrations of NAA, GA_3, and IAA at 30, 60, and 90 days after transplanting.

Treatment	Plant height (cm)		
	30 DAT	60 DAT	90 DAT
C	42.8ab	65.1bcd	69.6abc
NAA 20	35.1a	55.7a	62.1a
NAA 40	39.3ab	59.8ab	65.8ab
GA_3 10	51.1bc	71.6cd	76.8cd
GA_3 20	56.8c	74.4cd	79.4d
IAA 25	40.3ab	63.1abc	68.9abc
IAA 50	44.1ab	61.1ab	71.4bcd

Means with same letter within column are not significantly different according to Tukey HSD at $p < 0.05$.

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3.2 Flowering and fruit maturity

All PGR treatments accelerated flowering relative to the control. Untreated plants required 28.6 days to reach first flowering, whereas IAA at 50 mg L^{-1} reduced this period to 21.8 days, corresponding to a 23.8% reduction. NAA at 40 mg L^{-1} and IAA at 25 mg L^{-1} also promoted early flowering, requiring 23.4 and 23.6 days, respectively. GA_3 had a weaker influence on flowering than the auxin treatments, although both GA_3 concentrations still produced significantly earlier flowering than the untreated control. The PGR treatments also shortened the period from anthesis to successive fruit-maturity indices (Table 4).

IAA at 50 mg L^{-1} produced the earliest fruit development across all five maturity stages. Relative to the control, this treatment reduced the time required to reach maturity indices 1, 2, 3, 4, and 5 by 37.6, 27.5, 22.6, 18.5, and 17.1%, respectively. Fruits treated with IAA at 50 mg L^{-1} reached index 5 at 41.8 days after anthesis, compared with 50.4 days in the control. NAA at 40 mg L^{-1} produced a similarly strong response, with fruits reaching maturity index 5 at 42.4 days after anthesis. This represented a reduction of 8.0 days, or 15.9%, compared with the control. NAA at 40 mg L^{-1} was statistically comparable with IAA at 50 mg L^{-1} at most maturity stages, indicating that both auxins were effective in accelerating fruit development. The remaining treatments produced intermediate responses, although all generally shortened the maturity period compared with untreated plants.

The promotion of flowering and maturity by auxins can be explained by their central role in flower retention, ovary activation, fruit initiation, and early cell differentiation. In *Capsicum annuum*, auxin acts upstream of gibberellin biosynthesis during fruit set. Experimental inhibition of gibberellin synthesis substantially reduces fruit set, whereas subsequent GA_3 application restores it, demonstrating that auxin-induced fruit initiation is partly mediated through the gibberellin pathway (Tiwari et al., 2012). NAA may produce a more persistent response than IAA because it is a comparatively stable synthetic auxin, whereas endogenous IAA is more rapidly metabolised.

The early maturity induced by IAA at 50 mg L^{-1} did not, however, correspond to high yield. This treatment produced the earliest flowering and maturity but only a modest yield increase over the control. This divergence suggests that rapid phenological development and yield formation are physiologically distinct outcomes. Accelerated maturity may shorten the period available for assimilate accumulation or may alter the balance between fruit number, fruit growth, and fruit filling. Thus, earliness should be evaluated together with total yield and fruit quality when selecting a PGR treatment for commercial production.

Table 4. Days of first flowering, and from anthesis to successive fruit-maturity indices of Kulai chilli as influenced by NAA, GA_3, and IAA treatments.

Treatment	Days of first flowering	Days after anthesis to reach maturity index				
		Index 1	Index 2	Index 3	Index 4	Index 5
C	28.60e	21.8f	28.4e	35.4e	42.2d	50.4e
NAA 20	25.60c	17.0cd	24.4d	31.2c	38.4c	44.8cd
NAA 40	23.40b	14.6a	21.60ab	28.2a	35.4ab	42.4ab
GA_3 10	26.80d	18.4e	25.2d	32.2d	39.0c	46.2d
GA_3 20	25.60c	17.2de	23.2c	30.6c	38.2c	45.6cd
IAA 25	23.60b	15.8bc	22.2bc	29.2b	36.2b	44.0bc
IAA 50	21.80a	13.6a	20.60a	27.4a	34.4a	41.8a

Means with same letter within column are not significantly different according to Tukey HSD at $p < 0.05$.

3.3 Yield and physical fruit characteristics

PGR application significantly influenced yield per plant, individual fruit weight, and fruit length (Table 5). NAA at 40 mg L^{-1} produced the highest yield value of 6.8 per plant, representing a 61.9% increase over the control value of 4.2. NAA at 20 mg L^{-1} ranked second, with a yield of 5.5 per plant, followed by IAA at 25 mg L^{-1} and GA_3 at 20 mg L^{-1}, which produced values of 5.4 and 5.3, respectively. IAA at 50 mg L^{-1} produced only 4.5 per plant despite its strong promotion of flowering and maturity.

The yield advantage under NAA at 40 mg L^{-1} was accompanied by improvements in individual fruit size. This treatment produced the greatest mean fruit weight of 16.91 g, an increase of 18.6% over the control. NAA at 20 mg L^{-1} and GA_3 at 20 mg L^{-1} produced statistically comparable fruit weights of 16.51 and 16.50 g, respectively. Fruits from the NAA 40 mg L^{-1} treatment were also the longest, reaching 16.58 cm compared with 14.34 cm in the control, equivalent to a 15.6% increase. IAA at 50 mg L^{-1} produced a comparable fruit length of 16.19 cm, despite its comparatively low yield.

The enhanced yield under NAA at 40 mg L^{-1} was therefore associated with increased fruit length and individual fruit mass. NAA may have improved reproductive performance by strengthening fruit retention, stimulating cell division and enlargement during early fruit development, and increasing the sink capacity of developing fruits. Foundational physiological evidence in pepper shows that NAA induces greater fruit set than IAA while producing fruits of comparable size, potentially because of its longer persistence in plant tissues (Tiwari et al., 2012). More recent work also confirms that phytohormone treatments can significantly alter pepper fruit weight, length, thickness, yield, and biochemical quality (Fenn and Giovannoni, 2021; Moosavi et al., 2024).

The present response differs partly from that reported by Ahmed et al. (2022), who found that GA_3 at 30 mg L^{-1} produced the highest fruit set, yield, vitamin C, and capsaicin contents in the Chillina hot-pepper cultivar under plastic tunnels. In the current study, GA_3 predominantly stimulated vegetative growth, whereas NAA at 40 mg L^{-1} produced the most favourable reproductive response. These contrasting outcomes reinforce the cultivar-dependent nature of PGR responses and demonstrate that concentrations developed for one pepper genotype or production environment cannot be transferred directly to Kulai chilli without local evaluation.

Seed number ranged from 114.26 to 146.82 seeds per fruit, but no significant differences were detected among treatments. NAA at 40 mg L^{-1} produced the numerically highest seed number, whereas IAA at 50 mg L^{-1} produced the lowest. The absence of a significant seed response indicates that differences in fruit length and weight were not explained solely by seed number. Instead, PGR-mediated changes in pericarp growth, cell expansion, assimilate supply, or fruit sink strength probably contributed more strongly to the observed fruit-size responses.

Table 5. Yield, and fruit characteristics of Kulai chilli treated with different concentrations of NAA, GA_3, and IAA.

Treatment	Yield	Fresh weight (g)	Fruit length (cm)	No. of seeds per fruit
C	4.2a	14.26a	14.34a	129.20a
NAA 20	5.5d	16.51b	15.77bcd	140.58a
NAA 40	6.8e	16.91b	16.58e	146.82a
GA_3 10	4.9b	15.84ab	15.26b	129.96a
GA_3 20	5.3c	16.50b	15.9cd	138.44a
IAA 25	5.4cd	15.90ab	15.34bc	134.41a
IAA 50	4.5b	15.41ab	16.19de	114.26a

Means with same letter within column are not significantly different according to Tukey HSD at $p < 0.05$.

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3.4 Capsaicin and vitamin C

Fruit biochemical quality was strongly influenced by PGR treatment. NAA at 40 mg L^{-1} produced the highest reported capsaicin value of 27.80, representing a 65.5% increase relative to the control value of 16.80. NAA at 20 mg L^{-1} ranked second at 22.64, followed by GA_3 at 20 and 10 mg L^{-1} at 21.10 and 20.30, respectively. Both IAA treatments produced comparatively smaller increases in capsaicin, indicating that NAA exerted a stronger influence on pungency-related metabolism than IAA under the conditions tested. A similar treatment pattern was observed for vitamin C. NAA at 40 mg L^{-1} produced the highest reported vitamin C concentration of 158.47, which was 89.8% greater than the control value of 83.50. NAA at 20 mg L^{-1} also substantially increased vitamin C to 141.69. GA_3 at 20 mg L^{-1} produced a more moderate value of 96.39, whereas GA_3 at 10 mg L^{-1} and both IAA treatments did not differ significantly from the control (Table 6).

The simultaneous increases in yield, capsaicin, and vitamin C under NAA at 40 mg L^{-1} indicate that improved productivity was not achieved at the expense of biochemical quality. The response may reflect enhanced assimilate translocation towards developing fruits and hormonal regulation of metabolic pathways involved in organic-acid and secondary-metabolite biosynthesis. Lu et al. (2023) similarly found that manipulation of endogenous hormonal status in pepper increased yield while promoting the accumulation of soluble sugars, soluble proteins, vitamin C, and capsaicin. This supports the interpretation that PGRs affect fruit quality through interconnected hormonal, source–sink, and metabolic processes rather than through a single isolated pathway.

Nevertheless, capsaicinoid and vitamin C accumulation are strongly influenced by genotype, developmental stage, and the production environment. Recent phytochemical profiling demonstrated substantial cultivar-to-cultivar variation in capsaicinoid composition, with some local chilli cultivars containing two- to three-fold greater capsaicinoid abundance than a widely cultivated commercial genotype (Jang et al., 2024). Similarly, vitamin C metabolism changes during pepper fruit maturation and responds differently to agronomic inputs at mature-green and red-ripe stages (Zhang et al., 2023). Consequently, comparisons of biochemical quality across studies should consider cultivar, maturity at sampling, climate, nutrient management, and analytical methodology.

The findings also align with recent evidence that auxin–gibberellin combinations can increase pepper fruit weight, thickness, carotenoid accumulation, and vitamin C, although the magnitude of the response depends on crop load and management conditions (Moosavi et al., 2024). In that study, vitamin C was affected by the interaction between hormone treatment and pruning, illustrating that hormonal responses depend on the plant's broader source–sink balance.

Table 6. Capsaicin and vitamin C contents of Kulai chilli treated with different concentrations of NAA, GA_3, and IAA.

Treatment	Vitamin C (mg mL^{-1})	Capsaicin (SHU)
C	83.50a	16.80a
NAA 20	141.69c	22.64b
NAA 40	158.47d	27.80c
GA_3 10	84.65a	20.30d
GA_3 20	96.39b	21.10e
IAA 25	81.88a	17.30f
IAA 50	82.20a	19.50g

Means with same letter within column are not significantly different according to Tukey HSD at $p < 0.05$.

3.5 Integrated treatment response and agronomic implications

The three regulators produced clearly differentiated physiological responses. GA_3 at 20 mg L^{-1} was most effective for promoting vegetative growth, producing the tallest plants throughout the study. IAA at 50 mg L^{-1} was most effective for accelerating flowering and fruit maturity. In contrast, NAA at 40 mg L^{-1} provided the strongest overall agronomic response, combining earlier flowering and maturity with the highest yield, fruit weight, fruit length, capsaicin value, and vitamin C concentration.

These results demonstrate that greater vegetative growth does not necessarily maximise fruit productivity. Although GA_3 at 20 mg L^{-1} increased plant height by 14.1% at 90 DAT, its yield remained lower than that obtained with NAA at 40 mg L^{-1}. The superior performance of NAA suggests that reproductive sink establishment, flower or fruit retention, and assimilate allocation were more important determinants of yield than stem elongation under rain-shelter conditions.

From a production perspective, NAA at 40 mg L^{-1} showed the most favourable response under the conditions tested for Kulai chilli because it improved both marketable yield and nutritional or pungency-related quality. IAA at 50 mg L^{-1} may be useful where early harvest is the primary management objective, but its limited yield response reduces its suitability as a general productivity-enhancing treatment. GA_3 may be beneficial where greater plant vigour or canopy development is required, although excessive vegetative growth could increase competition between vegetative and reproductive sinks.

The results should nevertheless be interpreted within the scope of the experiment. The study was conducted during one production cycle at a single rain-shelter site and evaluated only two concentrations of each regulator. Moreover, the available dataset reports treatment means and Tukey groupings but does not provide standard errors, confidence intervals, ANOVA statistics, or exact p-values. Multi-location and multi-season trials are therefore required before formulating commercial recommendations. Future research should also evaluate application timing, dose–response relationships, repeated versus single applications, economic returns, fruit number, marketable yield, and possible interactions between PGRs and fertigation management.

4. Conclusion

The foliar application of plant growth regulators produced distinct growth, phenological, yield, and fruit-quality responses in Kulai chilli grown under rain-shelter conditions. GA_3 at 20 mg L^{-1} primarily promoted vegetative growth, producing the tallest plants throughout the cultivation period. In contrast, IAA at 50 mg L^{-1} accelerated flowering and fruit maturation, indicating its potential for shortening the production cycle. Among the treatments evaluated, NAA at 40 mg L^{-1} produced the most favourable overall agronomic response by combining earlier maturity with the highest yield, fruit weight, fruit length, capsaicin content, and vitamin C concentration. These findings demonstrate that greater vegetative growth does not necessarily translate into superior reproductive performance and that the agronomic value of a PGR treatment should be assessed using an integrated evaluation of growth, earliness, yield, and fruit quality. The findings should be interpreted cautiously because the experiment was conducted during a single production cycle at one rain-shelter location and evaluated only two concentrations of each PGR. Application timing, combined treatments, seasonal variation, and economic feasibility were not assessed. Future studies should validate the results across multiple seasons and locations, evaluate broader concentration ranges and application schedules, and include marketable yield, shelf life, capsaicinoid profiling, economic returns, and possible phytotoxicity.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

Jupikely James Silip: Conceptualization, resources, writing - review and editing, supervision, project administration. **Lydianie Wesley:** Writing - original draft, methodology, formal analysis, investigation. **Mohd. Rakib Mohd. Rashid:** Writing - review and editing. **Devina David:** Writing - review and editing.

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Conflicts of Interest

Jupikely James Silip and Mohd. Rashid Mohd. Rakib are the editors of this journal. To ensure an unbiased review process, the authors were recused from all editorial handling, peer review, and decision-making related to this article. The article was managed independently by another editor in accordance with the journal's editorial policies.

Ethics Statement

This study did not involve human participants, animal subjects, or identifiable personal data. Therefore, ethical approval was not required.

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