




ARTICLE

Morphophysiological changes and effects of exogenous plant growth regulators on the flower development of Siam tulip (*Curcuma alismatifolia*)

Alterações morfofisiológicas e efeitos de reguladores de crescimento exógenos no crescimento floral da cúrcuma (*Curcuma alismatifolia*)

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Abstract

The Siam Tulip (*Curcuma alismatifolia* Gagnep.) is a tropical ornamental plant capable year-round growth. However, its natural flowering is limited to the rainy season, thereby limiting its commercial viability as a continuously flowering ornamental crop. This study analyzed the morphological and physiological changes during the growth and development of plant propagated from corms and evaluated the effects of exogenous plant growth regulators on flower development in both juvenile and mature plants. The flower development of Siam Tulip can be divided into two distinct phases: (1) the floral transition phase (day 18 - 30), and (2) the flower development phase (day 30 to 72). The flower development included (i) floral organs formation and development (day 30 - 62), and (ii) inflorescence elongation and blooming (day 62 - 72). Levels of auxin, gibberellin, and cytokinin progressively increased from the vegetative to the reproductive stage, peaking during the late inflorescence development whereas abscisic acid levels rose from the vegetative phase to the floral meristem formation but gradual decline thereafter. Application of 20 mg L⁻¹ indole-3-acetic acid (IAA) or 10 mg L⁻¹ benzyladenine (BA) significantly accelerated floral initiation in juvenile plants and enhanced flower development in mature plants. Additionally, treatment with 20 mg L⁻¹ gibberellic acid promoted the elongation of the inflorescence stem. These findings suggest that appropriate PGR treatments can effectively accelerate flowering in *C. alismatifolia*, thereby enhancing its commercial potential.

Keywords: Flower development, flowering, inflorescence meristem, plant growth regulator.

Resumo

A cúrcuma (*Curcuma alismatifolia* Gagnep.) é uma planta ornamental tropical com capacidade de crescer durante todo o ano. No entanto, suas flores naturais florescem apenas durante a estação chuvosa, limitando assim seu potencial comercial como planta ornamental de floração contínua. Este estudo analisou as mudanças morfológicas e fisiológicas durante o crescimento e desenvolvimento de plantas derivadas de bulbos e avaliou os efeitos de reguladores de crescimento vegetal exógenos no desenvolvimento da flor nos estágios de plântula e adulto. O desenvolvimento da flor da cúrcuma pode ser dividido em dois estágios distintos: (1) estágio de transição da floração (dias 18 - 30), (2) estágio de desenvolvimento da flor (dias 30 - 72). O desenvolvimento da flor inclui (i) a formação e o desenvolvimento dos órgãos florais (dias 30 - 62), (ii) o alongamento e a antese da inflorescência (dias 62 - 72). As atividades de auxina, giberelina e citocinina aumentaram gradualmente do estágio vegetativo para o reprodutivo, atingindo o pico durante o desenvolvimento tardio da inflorescência, enquanto a atividade do ácido abscísico aumentou do estágio vegetativo para o estágio de formação do meristema floral, mas diminuiu gradualmente a partir daí. A aplicação de 20 mg L⁻¹ de indole-3-acetic acid (IAA) ou 10 mg L⁻¹ de benzyladenine (BA) promoveu significativamente a floração em plantas jovens e acelerou o desenvolvimento floral em plantas maduras. Além disso, o tratamento com 20 mg L⁻¹ de ácido giberélico também promoveu o alongamento das hastes da inflorescência. Esses resultados sugerem que o uso apropriado de reguladores de crescimento podem acelerar, de forma eficaz, o florescimento de *C. alismatifolia*, aumentando assim o seu potencial comercial.

Palavras-chave: Desenvolvimento floral, florescimento, meristema da inflorescência, reguladores de crescimento.

Introduction

Curcuma alismatifolia Gagnep., commonly known as Siam Tulip or Thai Tulip, is a flowering plant native to Thailand, Cambodia, Laos, and Myanmar. A member of the Zingiberaceae family, it is highly prized for its ornamental value, particularly its large, colorful bracts that resemble tulip flowers (Chao et al., 2025). The plant grows from rhizomes and is widely cultivated for decorative purposes, both in gardens and as a cut flower (Ewon and Bhagya, 2019). Siam Tulip can be successfully cultivated under Vietnamese climatic conditions, particularly blooming during the rainy season. However, the uneven timing and inconsistent quality of inflorescence pose challenges for commercial flower production. Therefore, achieving uniform and timely flowering is critical for enhancing its ornamental quality and market value.

Flower development is a complex process involving coordinated morphological and physiological transitions. In many plant species, plant growth regulators (PGRs) influence flowering by modulating floral transition, inflorescence initiation and development, thereby enabling control over flowering time and inflorescence quality (Kaur et al., 2021; Singh et al., 2023; Valleser, 2023; Chen et al., 2025; Naik et al., 2025).

Among these, auxins, gibberellins, and cytokinins play key roles. Auxin promotes floral initiation in tulip (Rietveld et al., 2000), and enhances flower development in saffron (Renau-Morata et al., 2021; Singh et al., 2023). Gibberellins are known its different roles in flowering in different species (Bauerle, 2021; Miura et al., 2024). Gibberellins act as major regulators in Arabidopsis, where they modulate florigen gene expression in the leaf and transfer to SAM and promote flowering in the SAM (Conti, 2017). Cytokinin promotes flowering in Arabidopsis through transcriptional activation of *TFS*, an *FT* paralog (D'Aloia et al., 2011) but delays flowering in rice (Cho et al., 2022). Moreover, cytokinin accumulation in the shoot apex under long-day conditions suggests its role as a systemic signaling molecule. Interactions between cytokinins and gibberellins have also been shown to regulate floral differentiation in *Dendrobium officinale* (Yin et al., 2025).

Although the individual roles of these hormones are well established in Arabidopsis and some ornamental species, their integrated effects on floral development in *Curcuma alismatifolia* remain largely unexplored. The strategic application of PGRs offers a promising approach to improve flowering uniformity and inflorescence quality, traits that

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are crucial for the commercial success of Siam Tulip. However, the underlying physiological and morphological mechanisms regulating floral development in this species, especially under tropical growing conditions, remain inadequately studied.

This study aims to fill these knowledge gaps by examining the morphophysiological responses of *C. alismatifolia* to exogenous PGRs. Specifically, it examines anatomical changes, carbohydrate metabolism, and hormonal interactions during floral development, providing a comprehensive understanding of how growth regulators can be utilized to optimize flowering quality and consistency in Siam Tulip.

Material and Methods

Plant material and growth condition

Corms of Siam Tulip which have about 20 mm in diameter were collected from flower farms and washed with water and planted in pots containing straw compost. Once the plantlets reached about 4 cm in height, they were transplanted into 18 cm diameter pots filled with 100% straw compost and cultivated in a garden under conditions of 30 - 33 °C temperature, 50% - 60% relative humidity, and 138 - 184 $\mu\text{mol m}^{-2} \text{s}^{-1}$ light intensity.

Tracking of plant growth and flower development of Siam Tulip

The growth of Siam Tulip was measured by growth parameters, including the number of leaves, leaf emergence timing, total leaf area, and pseudostem diameter. Leaves were numbered sequentially from the base to the tip. Leaf area was determined by analyzing leaf photographs using the Easy Leaf Area Android application. Flower development was evaluated based on inflorescence length and flowers number per bract. The pseudostem diameter and inflorescence length were measured using a ruler, with inflorescence length determined from the base to the tip. The experiment was arranged in a completely randomized design with three replicates, each consisting of ten pots, with one plant per pot. Growth and floral development parameters were measured individually for each plant.

Observation of morphological changes

Morphological changes during plant development were monitored and documented photographically from the juvenile stage to flowering. Changes in the shoot apical meristem (SAM) were observed by longitudinally sectioning of the shoot apex. Longitudinal histological sections were manually prepared using a razor blade. The sections were stained with a mixture of carmine red and iodine blue and observed under a light microscope at 4 \times and 10 \times magnifications. Images were captured using a Leica imaging system mounted on the microscope.

Measurement of photosynthetic intensity

The photosynthetic intensity ($\mu\text{mol O}_2 \text{ cm}^{-2} \text{ hour}^{-1}$) was measured using an oxygen electrode (LeafLab2, Hansatech Instruments, UK), based on the rate of change in oxygen concentration within the measurement chamber over time, conducted at a temperature of 27 ± 2 °C with a cooling system, and under a light intensity of $184 \mu\text{mol m}^{-2} \text{ s}^{-1}$. The reported values represent the mean of three replicates measured on three different leaves.

Measurement of sugar and starch content

The soluble sugar and starch contents in the leaves and apical buds were quantified based on the colorimetric reactions of sucrose and glucose. Absorbance was measured using a UV-Vis spectrophotometer (UV-2602, USA) at wavelengths of 490 nm and 530 nm, following the method described by Masuko et al. (2005). The values represent the mean of three replicates measured on three different explants.

Measurement of phytohormones

Phytohormone extraction and quantification were carried out to determine endogenous hormone dynamics throughout the transition from the vegetative to the reproductive phase. Phytohormones in plant buds at different developmental stages, from the vegetative to the reproductive phase, were extracted using 80% methanol. Hormone isolation followed the pH-dependent diethyl ether extraction method described by Meidner (1984), and Loveys and Van Dijk (1998). Thin-layer chromatography (TLC) was performed on silica gel plates (TLC 60 F254, Merck) to separate auxin, cytokinin, gibberellin, and abscisic acid (ABA). Hormones were visualized under UV light at 545 nm and identified by comparison with standard references (IAA, zeatin, GA_3 , and ABA) as described by Yokota et al. (1980).

Bioassays were conducted to evaluate hormonal activity, using rice coleoptile segments for auxin and ABA, cucumber cotyledons for cytokinin, and lettuce hypocotyls for gibberellin. Auxin and abscisic acid contents were determined from coleoptile elongation after 24 h relative to 1 mg L⁻¹ IAA and ABA standards, respectively. Cytokinin content was estimated from the increase in cotyledon fresh weight after 48 h under illumination, using a 1 mg L⁻¹ zeatin standard. Gibberellin content was assessed from mesophyll elongation after 5 days, using a 10 mg L⁻¹ GA_3 standard (Meidner, 1984; Tran et al., 2025).

Treatments of exogenous plant growth regulators on the flowering

To investigate the effects of exogenous PGRs on flowering, plants at 15 and 30 days of age were treated by foliar application of 20 mg L⁻¹ IAA, 20 mg L⁻¹ GA_3 , 10 mg L⁻¹ BA, or a combination of all three (IAA, GA_3 , and BA). Tween 20 (0.01%) was incorporated into the solution to enhance dispersion and adhesion, thereby increasing steaming efficiency. Treatments were applied daily at 8:00 am by spraying the entire leaves surface, using 1 mL per plant for 15-day-old plants and 3 mL per plant for 30-day-old plants. Flower development was observed from the initiation of treatment until inflorescence emergence. The percentage of flowering plants was recorded on day 55, and the number of leaves, number of flowers, and inflorescence length were measured on day 68. The experiment was conducted using a completely randomized design. Each treatment consisted of three replicates, with five plants per replicate. Floral development parameters were measured individually for each plant.

Statistical analysis

Data were statistically analyzed using SPSS software (IBM SPSS Statistics) version 22.0 for Windows with one-way ANOVA. Differences between means were considered statistically significant at $p \leq 0.05$. For leaf area at day 20 data, the Student's *t*-test were applied at $p \leq 0.05$.

Results

Plant growth and flower development

Morphological changes

The growth of Siam Tulip from corms to mature plants occurred in approximately 60 days. The plant has a pseudostem formed by the leaves and leaf sheaths (Fig. 1A). The first leaf fully opened on day 15 after planting. During the first 15 days of growth, the leaf sheaths tightly enclosed the pseudostem (Fig. 1B). The plant continued to produce the second leaf on day 20, the third leaf on day 30, and reached a maximum of six leaves on day 60. From day 18 onward, the basal leaf sheaths began to open (Fig. 1C). By day 30, the first three leaves were fully expanded, and all the lower sheaths were visibly opened (Fig. 1D). By day 50, the plant had five fully opened leaves, and the inflorescence was established but still covered by the pseudostem. The final leaf (sixth) emerged on day 60 (Fig. 1A). The pseudostem diameter increase slowly during the first 15 days, then sharply increased from day 20, reaching its peak on day 60 before slightly decreased by day 63 (Fig. 1E).

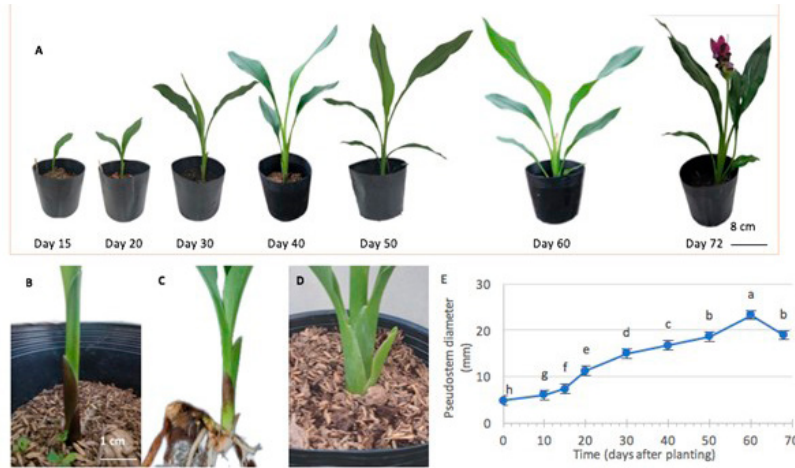


Fig. 1. The development of Siam Tulip plant, from vegetative to flowering: **A.** Plant at day 15, 20, 30, 40, 50, 60, and 72. **B-D.** The leaf sheaths enclosed the pseudostem on day 15 (**B**), began to open by day 18 (**C**), and were fully opened by day 30 (**D**). **E.** Changes in pseudostem diameter of plant during development. Different letters in the graph indicate significant differences at the $p \leq 0.05$ level

During the first 15 days after planting, microscopic observation revealed that the SAM at the apex of the Siam tulip was in the vegetative phase, characterized by a dome-shaped structure (Fig. 2A). By day 18, the SAM had increased in both width and height, with the apex becoming distinctly pointed (Fig. 2B, Fig. 2F). By day 30, the apical meristem had transitioned into an inflorescence meristem, exhibiting a sharp apex and initiating the formation of secondary inflorescence meristem primordia (Fig. 2C). These secondary meristems arose from the axils of the primary inflorescence meristem and gave rise to approximately 3 to 4 floral meristems along with bract primordia. At each position of the purple-green bracts, these floral meristems initiated floral primordia, which subsequently developed into floral organs by day 57 (Fig. 2D).

At this stage, all morphological changes remained internal and were not externally visible. The inflorescence first became visible at the shoot apex on day 62. From day 62 to day 72, it continued to elongate, reaching its maximum height by day 72, at which point all flower buds had fully opened (Fig. 2E, G). The inflorescence consists of two distinct bract types, differing in both shape and color: green-purple bracts at the base and pink bracts at the apex (Fig. 2E). Flowers emerge from the axils of the green-purple bracts, with each bract supporting approximately 4 to 8 flowers. In contrast, the axils of the pink bracts do not bear flowers, though they contain rudimentary undeveloped floral structures (Fig. 2H). The blooming process proceeded sequentially from the basal green-purple bracts upward the apical ones.

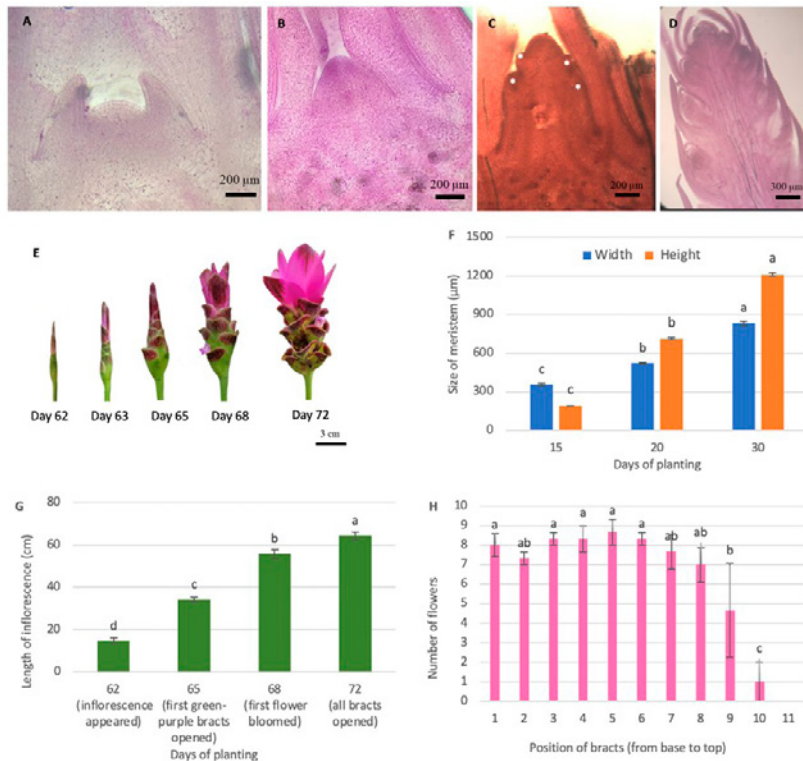


Fig. 2. The inflorescence development of Siam Tulip plant: **A-D.** Longitudinal sections through the meristematic tissue. **A.** vegetative meristem on day 15, **B.** inflorescence meristem with sharp apex on day 18, **C.** inflorescence meristem with sharp apex and 4 secondary inflorescence meristems on day 30, **D.** inflorescence meristem with some secondary inflorescence meristems and bract primordia on day 57. In each axil of bracts, there are floral formation with primary of floral organs. **E.** inflorescence development from day 62 to 72. **F.** changes of apical meristem size from vegetative to reproductive phase, **G.** changes in length of inflorescence stem, **H.** the number of flowers from each bract of inflorescence at day 68. Different letters in the graphs indicate significant differences at the $p \leq 0.05$ level

Changes in photosynthetic intensity

The leaf area increased gradually from the base to the tip of plant. The photosynthetic intensity of the first leaf increased slightly from day 15 to day 20, corresponding to the changing from the vegetative phase to the

floral transition. Then, it gradually declined by day 30 before rising again at day 60 during the inflorescence elongation phase. At day 30, the third leaf exhibited the highest photosynthetic intensity, whereas by day 60, the peak value was recorded in the fifth leaf (Table 1).

Table 1. Leaves development and photosynthetic intensity at various plant ages of the Siam Tulip

Leaf position	Leaf-out time (day)	Leaf area (cm ²)				Photosynthetic intensity (μmol O ₂ /cm ² /hour)			
		Day							
		15	20	30	60	15	20	30	60
1	15.20 ^f	32.55	33.40	34.20 ^c	34.32 ^f	8.28	10.92	5.70 ^{ab}	15.18 ^c
2	19.80 ^e	-	50.68 [*]	51.13 ^b	51.28 ^e	-	8.04	5.46 ^b	28.32 ^b
3	29.50 ^d	-	-	76.34 ^a	77.36 ^d	-	-	9.12 ^a	25.92 ^b
4	39.84 ^c	-	-	-	94.94 ^c	-	-	-	27.18 ^b
5	49.00 ^b	-	-	-	129.22 ^b	-	-	-	49.86 ^a
6	58.50 ^a	-	-	-	146.28 ^a	-	-	-	17.88 ^c

The means in the column followed by different letters are significantly different at the $p \leq 0.05$ level.

*: means in the column are different in Student's *t*-test at the $p \leq 0.05$

(-): leaf has not appeared yet

Changes in sugar and starch content

At day 30, the plant had developed three leaves, and although the inflorescence was not yet visible to the naked eye, its primordia had already initiated. During this stage, the soluble sugar content increased progressively from the first to the third leaf, whereas starch content showed an inverse trend. The third leaf exhibited the highest level of soluble sugars and the lowest starch content, while the first leaf showed the lowest level of soluble sugars and the highest starch accumulation (Fig. 3 A and B).

In the apical buds, the concentrations of soluble sugars and starch changed throughout the developmental phases from the vegetative stage (day 15), through the floral transition (day 20), to the initiation of inflorescence (day 30). The sugar concentration in apical buds peaked at day 30, corresponding to the onset of inflorescence initiation, and was lowest at day 20 during the floral transition. Meanwhile, starch content gradually increased from day 15 to day 20 and rose sharply by day 30 (Fig. 3 C and D).

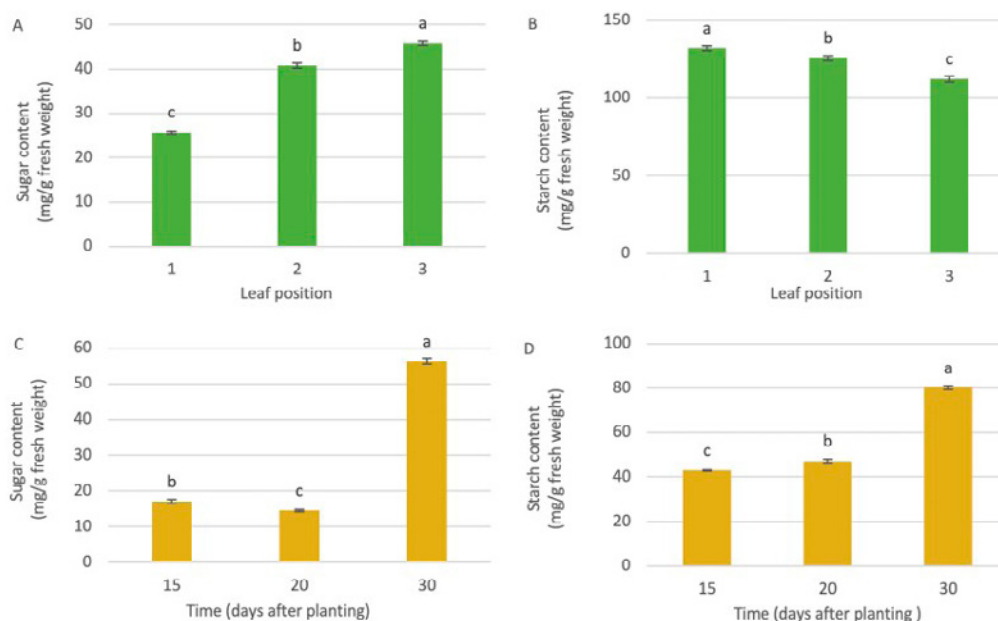


Fig. 3. Changes in soluble sugar and starch content in leaves and apical buds of the Siam Tulip. **A.** Sugar content in leaves at day 30, **B.** Starch content in leaves at day 30, **C.** Sugar content in apical buds from day 15 to 30, **D.** Starch content in apical buds from day 15 to 30. Different letters in the graphs indicate significant differences at the $p \leq 0.05$ level

Changes in phytohormones level

The activity level of auxin increased gradually from vegetative to flowering. Auxins content in the shoot at day 15 was the lowest while auxins in the inflorescence at day 60 was the highest. Auxins increased rapidly during the formation of floral meristem (day 20) and peaked during the development of floral organs and elongation inflorescence (day 30 and 60). The activity level of cytokinin and gibberellin (GA) in the

shoot were the lowest during the vegetative phase and increased slowly but steadily during the formation of floral meristem and the development of inflorescence. Abscisic acid (ABA) increased in the shoot from the vegetative phase to the formation of floral meristems, then decreased sharply, reaching its lowest level during the development of floral organs and elongation inflorescence (Table 2).

Table 2. The levels of phytohormones in the apical buds of the Siam Tulip at different growth stages.

Day of culture	Levels of phytohormones (mg L ⁻¹)			
	Auxin	Cytokinin	Gibberellin	ABA
15	0.50 ^d	2.28 ^c	0.77 ^c	2.07 ^{ab}
20	0.82 ^c	2.74 ^{bc}	1.40 ^{bc}	2.66 ^a
30	1.18 ^b	3.16 ^{ab}	2.21 ^{ab}	1.25 ^{bc}
60	1.54 ^a	3.77 ^a	3.08 ^a	0.83 ^c

The means in the column followed by different letters are significantly different at the $p \leq 0.05$ level.

Effects of exogenous plant growth regulators on flower development

All treatments with exogenous PGRs applied to both juvenile (15-day-old) and mature (30-day-old) plants induced earlier flowering compared to the control. In juvenile plants, the application of 10 mg L⁻¹ BA resulted in the earliest flowering, achieving a 100% flowering rate in the day 55. Similarly, treatment with 20 mg L⁻¹ IAA also effectively promoted early flowering. The application of 20 mg L⁻¹ GA₃, or the combination of IAA (20 mg L⁻¹), GA₃ (20 mg L⁻¹), and BA (10 mg L⁻¹) had a lesser effect on flowering rates (Table 3). Among all treatments on mature plants, the application of 10 mg L⁻¹ BA or 20 mg L⁻¹ IAA promoted

the earliest flowering (approximately 93.33%) while 20 mg L⁻¹ GA₃ or the combination of IAA (20 mg L⁻¹), GA₃ (20 mg L⁻¹), and BA (10 mg L⁻¹) also stimulated early flowering with a lower flowering rate (Table 3). IAA at a concentration of 20 mg L⁻¹ significantly reduced the flower development time, including both inflorescence initiation and development. Treatment with 10 mg L⁻¹ BA induced inflorescence emergence later than 20 mg L⁻¹ IAA but promoted the fastest inflorescence development among all treatments. GA₃ at 20 mg L⁻¹ prolonged the inflorescence development time. While the combination treatment of IAA (20 mg L⁻¹), GA₃ (20 mg L⁻¹), and BA (10 mg L⁻¹) stimulated flowering, it also resulted in a longer inflorescence development time compared to the control (Fig. 4A).

Table 3. Effect of exogenous plant growth regulators applied at different growth stages on flowering percentage at day 55 of the Siam Tulip.

Plant growth regulators	Percentage (%) of flowering	
	juvenile plants	mature plants
Control (distilled water)	0.00 ^d	0.00 ^d
20 mg L ⁻¹ IAA	86.67 ^a	93.33 ^a
20 mg L ⁻¹ GA ₃	53.33 ^b	46.67 ^b
10 mg L ⁻¹ BA	100 ^a	93.33 ^a
20 mg L ⁻¹ IAA, 20 mg L ⁻¹ GA ₃ , and 10 mg L ⁻¹ BA	26.67 ^c	20.00 ^c

The means in the column followed by different letters are significantly different at the $p \leq 0.05$ level.

Regarding inflorescence characteristics, the greatest number of pink bracts was observed in plants treated with 10 mg L⁻¹ BA, while the control group exhibited the lowest. No significant differences were found among the remaining treatments (Fig 4B). The number of flowers per inflorescence was recorded in the BA treatment was higher than in the GA treatment, with no significant differences among the treatments and control (Fig 4C). All applications of exogenous PGRs enhanced

inflorescence elongation compared to the control, both in terms of emergence and cessation. The longest inflorescence stem was observed in the treatment with 20 mg L⁻¹ GA₃, while all other treatments also showed greater stem length than the control. The maximum inflorescence length was achieved in the treatments with 20 mg L⁻¹ GA₃ and the combination of 20 mg L⁻¹ IAA, 20 mg L⁻¹ GA₃, and 10 mg L⁻¹ BA (Fig. 4 D, E).

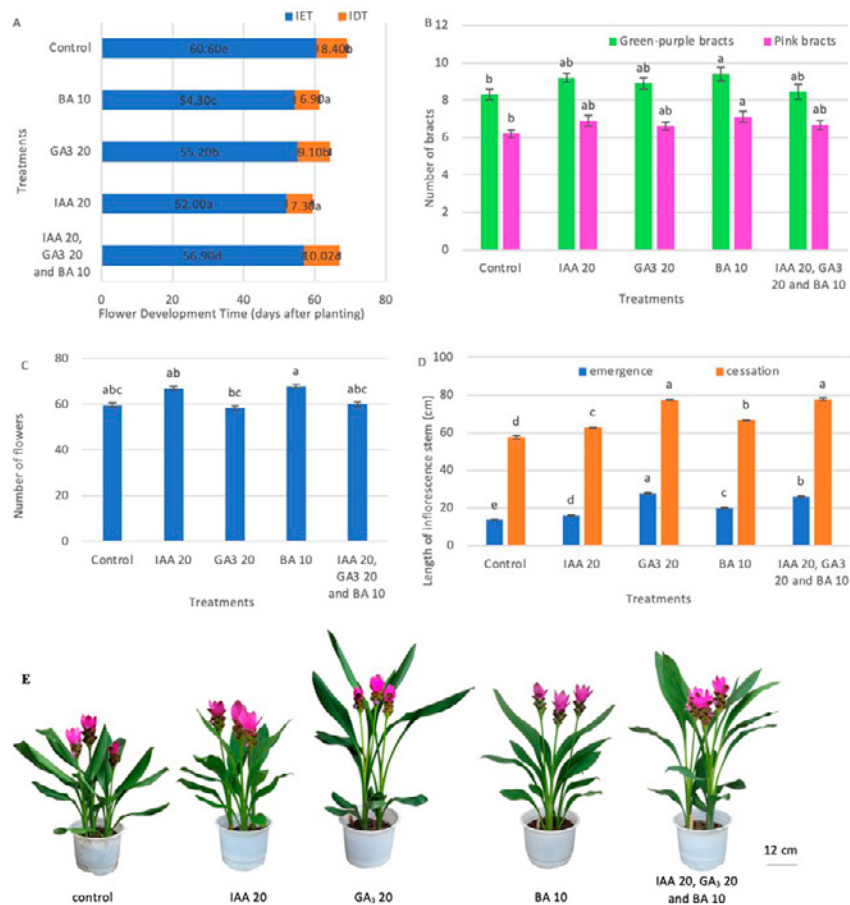


Fig. 4. Effects of exogenous PGRs on inflorescence development of mature plant of the Siam Tulip on day 68: **A.** Total time of flowering, **IET.** Inflorescence emergence time, **IDT.** inflorescence development time, **B.** number of bracts of the inflorescence, **C.** number of flowers of the inflorescence, **D.** length of inflorescence stem, **E.** plants in treatment with exogenous PGRs. Different letters in the graphs indicate significant differences at the $p \leq 0.05$ level

Discussion

Morphogenesis of plant growth and flowering

The Siam tulip development can be divided into three distinct phases: (1) the vegetative growth, (2) the floral transition, and (3) the flower development. The flower development phase consists of two stages: (i) floral organs formation and development, and (ii) inflorescence elongation and blooming.

The vegetative growth phase (0 - 18 days after planting) is characterized by leaf emergence and gradual pseudostem elongation (Fig 1A-C, Fig. 2A). During this period, plants typically produce two leaves whose sheaths encase the shoot to form the pseudostem. The shoot apical meristem (SAM) remains in a dome-shaped vegetative state, and pseudostem diameter increases slowly. Around day 18, the basal leaf sheaths begin to open, and by day 20, the SAM enlarges and becomes pointed (Fig. 2A), signaling the onset of floral transition.

The floral transition phase (days 18 - 30), marking the inflorescence formation (Fig 1A, D). During this period, the SAM transitions into the primary inflorescence meristem, which has a sharp, pointed structure and increasing further in both width and height (Fig. 2A, B). Typically, the SAM in the vegetative phase is dome-shaped and responsible for shoot, leaf, and stem development, with active cell division in the peripheral and rib zones and relative dormancy in the central zone. In the reproductive phase, the size and structure of the meristem change due to enhanced cell division and differentiation (Force et al., 2025). If the meristem expands more in width, it adopts a flattened appearance. In contrast, if the meristem expands in height, it becomes pointed. In Siam Tulip, the apical meristem increases in both width and height as it transitions to the reproductive phase. Additionally, the conspicuous widening of leaf sheaths may serve

as a morphological indicator of the flowering transition, even when the inflorescence remains internally concealed.

The flower development phase (days 30 - 72), including floral organs formation and development (days 30 - 62), and inflorescence elongation and blooming (days 62 - 72). During this period, the plant produces four additional leaves at a faster rate than during the vegetative phase, with each leaf requiring approximately 10 days to fully expand (Fig. 1A, 2C and D).

From days 30 - 62, the pseudostem diameter expands markedly as the primary inflorescence meristem generates secondary inflorescence meristems, which in turn initiate floral meristems that differentiate into floral organs and form flower buds. The sequential initiation of secondary inflorescence meristems and subsequent floral meristems aligns with patterns reported in *Curcuma longa* and *Zingiber officinale*, suggesting conserved morphogenetic control within the *Zingiberaceae* family (Hwang et al., 2014). Although these internal transformations are not externally visible, the rapid expansion of pseudostem diameter provides indirect evidence of active meristematic and vascular differentiation that supports reproductive growth. By day 60, the inflorescence becomes visible.

Between days 62 and 72, continuous elongation of the inflorescence was observed until all pink bracts were fully expanded. The inflorescence exhibited two morphologically distinct bract types: green-purple bracts at the base and pink bracts at the apex. This color transition likely reflects increased anthocyanin accumulation associated with floral maturation and reproductive competency. Floral emergence followed a highly ordered sequence, initiating from the axils of the basal pink bracts and progressing upward. Each bract produced 4 - 8 florets, consistent with previous observations in *Curcuma alismatifolia* by Hwang et al. (2014),

who reported floret initiation once 5 - 7 bracts had formed. The sequential blooming from basal to apical bracts suggests a hierarchical developmental regulation along the inflorescence axis, possibly governed by hormonal or positional gradients influencing sink–source dynamics and resource allocation during late floral development.

Photosynthetic and carbohydrate dynamics during flowering

During the vegetative growth phase, the first two leaves exhibited higher levels of photosynthetic activity compared to the floral transition phase, although still lower than those observed during the flowering development phase. By day 30, the beginning of flower development, the third leaf showed the highest photosynthetic intensity among the three existing leaves. At this time, it also contained the highest sugar content and the lowest starch accumulation. These results indicate that, during the vegetative phase, mature leaves function as primary sources of photosynthates, providing energy and metabolites essential for plant growth. As the plant enters the floral transition phase, photosynthetic activity in the leaves slightly declines. However, the most recently developed leaf (the third leaf) maintains the highest photosynthetic rate, indicating its critical role in providing energy for floral initiation. This physiological shift is further substantiated by changes in carbohydrate metabolism: sucrose produced via photosynthesis in the leaf is predominantly translocated to the shoot apex to fulfill the elevated energy demands of flower development, rather than being stored as starch within the leaf tissue. Consistent with this redistribution, both sucrose and starch contents in the shoot apex increased markedly at day 30 compared to earlier stages (days 15 and 20), showing an indicating a directed allocation of photosynthetic products toward the developing inflorescence. Sucrose functions not only as a carbon source but also as a signaling molecule that mediates flowering induction. The elevated sucrose concentration at the shoot apex coincides with the onset of floral development, consistent with reports that sucrose promotes floral initiation in rice (Cho et al., 2024), stimulates floral bud differentiation in lily (Pan et al., 2025), and enhances flowering in blueberry (Wu et al., 2025). These findings reinforce the dual regulatory and metabolic roles of sucrose in coordinating the transition to flowering.

Roles of plant growth regulators on flowering

The activity of auxin in the shoot apex increased markedly during the floral transition and peaked during the floral organ formation and development stages. These significant fluctuations highlight the crucial role of auxin in regulating flowering. Auxin stimulates cell division and differentiation within the apical meristem, thereby facilitating the initiation of floral primordia.

The elevated endogenous auxin activity during floral transition and organ formation indicates that auxin serves as a central regulator of flowering in Siam Tulip, coordinating both floral induction and inflorescence development. Among the PGRs treatments, application of 20 mg L⁻¹ exogenous IAA induced the earliest flowering, shorten not only the inflorescence emergence time but also the inflorescence development time. However, the number of bracts and flowers did not significantly exceed that of the control group, suggesting that the principal effect of exogenous IAA lies in accelerating floral transition rather than enhancing flower formation.

Cytokinin activity in the shoot apex showed a pattern similar to that of auxin, although its increase occurred more gradually. Cytokinin is well known to promote cell division within the apical meristem and has been implicated in the transition from vegetative to reproductive growth (Barbosa and Dornelas, 2021; Werner et al., 2021). In saffron, cytokinin stimulates flowering by downregulating flowering repressor genes and upregulating floral developmental genes (Singh et al., 2023). In this study, cytokinin levels increased slightly between days 20 and 30, coinciding with the floral transition phase, suggesting a supportive role in floral induction. During floral organ formation and development (days 30–60), characterized by intensified cell division, endogenous cytokinin levels continued to rise and peaked at day 60, enhancing cell proliferation in the reproductive meristem. Furthermore, treatment with 10 mg L⁻¹ BA not only promoted early flowering in both juvenile and mature plants but also resulted in the highest number of both green and pink bracts and increased inflorescence stem length. These findings corroborate

the observations of Yan et al. (2025), who reported that exogenous BA promotes flower formation and development in *Phalaenopsis*. Thus, exogenous BA significantly contributes to both floral initiation and structural development of the inflorescence in Siam Tulip.

The influence of gibberellins (GAs) on flowering is species- and concentration-dependent. GA₃ promotes early flowering in *Dianthus* (Ayesha et al., 2020), *Dendrobium*, and *Cymbidium* (Yin et al., 2025), whereas it delays flowering in crops such as mango (Turnbull et al., 1996) and saffron (Singh et al., 2023). In calla lily, GA₃ at 100 mg L⁻¹ induces early flowering, while higher concentrations (200 mg L⁻¹) delay it (Chandel et al., 2023). Conversely, Boontiang et al. (2021) reported that paclobutrazol, a gibberellin biosynthesis inhibitor, reduced plant height and inflorescence length but promoted earlier flowering in off season *Curcuma alismatifolia*. The GA₃ concentrations used in these studies were higher than those applied in our experiment. In our results, application of 20 mg L⁻¹ GA₃ also promoted early flowering compared to the control but it did not alter the duration of inflorescence development. Notably, the effect of exogenous GA₃ on flowering was weaker than that of IAA or BA. These findings suggest that GA₃ does not play a major role in floral induction but instead facilitates inflorescence development by enhancing elongation. Consistently, endogenous GA₃ levels remained stable low during the floral transition but increased sharply during inflorescence development. Gibberellin stimulates both cell division and elongation, particularly in the rib zone of the meristem (Chaudhry et al., 2024), thereby promoting inflorescence stem elongation and supporting inflorescence development. Thus, in Siam Tulip, GA₃ mainly contributes to inflorescence emergence rather than floral induction, which explains why exogenous GA₃ shortened the time to inflorescence emergence without affecting inflorescence development duration. GA₃ application should be optimized to balance early flowering with commercially desirable inflorescence traits, as stem elongation can enhance cut flower appeal but may limit suitability for pot cultivation.

Conclusions

Siam Tulip flowering begins on day 18 and progresses through floral transition and flower development, with basal green-purple bracts bearing flowers and sterile apical pink bracts. During flowering, the concentration of soluble sugar, the activities of auxin, cytokinin, and gibberellin are elevated, while abscisic acid activity decreases. Exogenous 10 mg L⁻¹ BA or 20 mg L⁻¹ IAA effectively promote early flowering on both juvenile and mature plants. BA has a stronger effect on juvenile plants, whereas IAA more strongly promotes flowering in mature plants. Treatment with 10 mg L⁻¹ BA also significantly enhances inflorescence development by increasing early flowering rates, accelerating inflorescence growth, and elevating the number of bracts and flowers. Application of 20 mg L⁻¹ gibberellic acid promotes inflorescence elongation.

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Author Contribution

CTT: Conceptualization, Methodology, Formal Analysis, Writing - Original Draft. **PAMN:** Conceptualization, Data Curation, Formal Analysis, Investigation. **THT:** Conceptualization, Methodology, Formal Analysis, Writing - Review & Editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Data will be made available upon request to the authors.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the use of AI and AI-assisted technologies was not applied in the writing process.

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