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Regulation of flowering and fruit development in red dragon fruit (*Hylocereus polyrhizus*) through gibberellic acid under off-season

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ABSTRACT

This study aims to evaluate the effect of gibberellin (GA_3) on the regulation of flowering and fruit development of red dragon fruit (*Hylocereus polyrhizus*) during the off-season period. The research was conducted in Banyuwangi, Indonesia, using a single-factor Randomized Block Design (RBD) consisting of five GA_3 concentrations: 0, 200, 400, 600, and 800 ppm. The observed parameters included the time to first flowering, number of flowers, number of fruits, fruit weight, fruit volume, peel thickness, sugar content (°Brix), and anthocyanin content. Analysis of variance showed that GA_3 application had a highly significant effect ($p < 0.01$) on flowering time, flower and fruit number, fruit weight, and fruit volume, but did not significantly influence peel thickness or sugar content. Concentrations of 400–600 ppm produced the most favorable physiological responses, accelerating flowering time, increasing flower and fruit numbers by up to twofold compared with the control, and significantly enhancing fruit weight and volume. A negative correlation between GA_3 concentration and flowering time ($r = –0.81$*) indicated accelerated generative transition, while a positive correlation between GA_3 and yield ($r = 0.92$*) confirmed improved reproductive efficiency. These mechanisms are theoretical explanations based on existing models and literature, rather than direct measurements of gene expression or protein activity in this study. These findings demonstrate that GA_3 application at 400–600 ppm can serve as an effective agronomic strategy to extend the production period, increase yield, and maintain fruit quality of red dragon fruit under tropical off-season conditions.

Keywords: gibberellin (GA_3), *Hylocereus polyrhizus*, off-season flowering, anthocyanin.

INTRODUCTION

Red dragon fruit (*Hylocereus polyrhizus*) is a high-value tropical horticultural commodity widely cultivated across Southeast Asia, including Indonesia. Its popularity has increased due to its rich nutraceutical profile – high in antioxidants, betacyanins, vitamin C, fiber, and various bioactive compounds with demonstrated anticancer and cardioprotective properties (Yadav et al., 2024). Beyond its nutritional benefits, this species is known for its strong adaptability to arid conditions, its crassulacean acid metabolism (CAM) photosynthetic system, and its tolerance to environmental stresses, making it highly suitable for cultivation in marginal lands (Jadhav et al., 2025).

Despite its agronomic potential, the productivity of red dragon fruit remains constrained by a strictly seasonal flowering pattern, occurring only from May to October in the Northern Hemisphere. This limitation is closely related to the plant's sensitivity to photoperiod, as *H. polyrhizus* is classified as a long-day plant whose floral induction is triggered when day length exceeds 12 hours (Jiang et al., 2012). Outside this natural photoperiodic window, flowering rarely occurs, resulting in strongly seasonal production, market supply instability, and price fluctuations in global trade (Yadav et al., 2024).

Plant physiological studies have shown that photoperiod and ambient temperature are the primary environmental cues regulating the vegetative-to-generative transition in *Hylocereus* spp. (Sin et al., 2023). Jiang et al. (2012) confirmed that *H. polyrhizus* requires long-day conditions: shortening the photoperiod to eight hours suppresses floral bud formation and enhances vegetative growth. Conversely, night-breaking or supplemental illumination for four hours during the night successfully induces flowering outside the natural season. These findings highlight that artificial photoperiod manipulation may serve as an effective strategy to extend the flowering period and off-season fruit production.

In addition to photoperiodic control, flowering and fruit development are also regulated by plant hormones, particularly gibberellins (GA_3). Gibberellins play crucial roles in cell elongation, dormancy breaking, and floral induction through the activation of floral meristem identity genes (Wang et al., 2024). In various tropical fruit crops, exogenous GA_3 application has been reported to prolong the flowering period, increase the number of perfect flowers, and improve fruit size and quality (Sin et al., 2023).

In dragon fruit, previous studies show that GA_3 application during the vegetative phase accelerates stem elongation and increases biomass by up to 54.69% (Chen et al., 2023). Meanwhile, GA_3 treatment during the flowering phase may extend the generative period and enhance yield, although its physiological response varies depending on dosage and timing (Jadhav et al., 2025). Several studies also recommend the combined use of GA_3 with artificial light or temperature manipulation to achieve synchronized off-season flowering (Jiang et al., 2012; Yadav et al., 2024).

The major challenge in red dragon fruit production is the low success rate of flowering and fruit set during the off-season, largely due to limited understanding of the physiological mechanisms governing the interaction between light, temperature, and plant growth regulators. Therefore, exploring flowering regulation mechanisms through GA_3 application under off-season conditions is highly relevant. This approach is expected to extend the reproductive window, increase annual productivity, and support the year-round availability of red dragon fruit (Jadhav et al., 2025; Yadav et al., 2024). The present study aims to analyze the role of gibberellin (GA_3) in inducing and regulating flowering of *H. polyrhizus* under off-season tropical conditions.

MATERIALS AND METHODS

This study was conducted from July to October 2024 in Bulurejo Village, Purwoharjo District, Banyuwangi Regency, Indonesia, at an elevation of approximately 100 meters above sea level. The research site is characterized by latosol soil type, with an average monthly rainfall of 153.5 mm, an average temperature of 27 °C, and a relative humidity of 80%.

A single-factor randomized block design (RBD) was employed, with the plant growth regulator gibberellin (GA_3) as the treatment factor. Five concentration levels were tested: G_0 = 0 ppm, G_1 = 200 ppm, G_2 = 400 ppm, G_3 = 600 ppm, and G_4 = 800 ppm. Each treatment was replicated four times, using three planting posts per replicate, with three plants per post (nine plants per treatment). In total, 180 plants (60 posts) were used, of which 120 plants served as experimental samples.

The materials used included five-year-old red dragon fruit plants (*Hylocereus polyrhizus* var. Red Rose), LED lamps, NPK fertilizer, and GA_3 solutions according to the treatment levels. The LED used is a yellow LED with a power of 12 watts and a lighting duration of 6 hours (17:00–23:00). LED lamps were installed at a height of approximately 30 cm above the plant canopy. NPK fertilizer was applied at 20 g plant^{-1} monthly, irrigation was carried out every seven days, and weed, pest, and disease control was conducted as required. GA_3 using liquid product that has been formulated into a stock solution with a concentration of 1000 ppm, which is then diluted according to the desired treatment concentration using the equation $C1 \times V1 = C2 \times V2$ (C1: Initial (concentrated) solution concentration; V1: Volume of the initial (concentrated) solution taken; C2: Desired final (diluted) solution concentration; V2: Total volume of the final solution (concentrated solution + solvent) to be prepared). The solvent used for dilution is aquades. In this study, no surfactant is used as the research is conducted during the dry season. GA_3 was applied by foliar spraying at a volume of 250 mL plant^{-1} every seven days.

The pollination method used in this study is manual pollination, specifically through self-pollination in dragon fruit. Self-pollination in dragon fruit occurs when the flower's male and female reproductive organs are capable of fertilizing the same flower, though manual intervention is sometimes necessary to ensure successful pollination.

The following parameters were recorded: (1) days to flowering (when 50% of plants had flowered); (2) total number of flowers per plant (recorded every 15 days); (3) fruit number per plant; (4) fruit volume measured using the water displacement method; (5) fruit weight measured with a digital scale; (6) soluble solids content (°Brix) measured using a refractometer; and (7) anthocyanin content (%) determined from 100 g of fresh pulp using spectrophotometric analysis at the Sucofindo Laboratory.

The collected data were analyzed using analysis of variance (ANOVA) following the randomized block design. When significant differences were detected (F-calculated > F-table at 5%), mean separation was performed using the honestly significant difference (HSD) test at the 5% level; and when highly significant differences were observed (F-calculated > F-table at 1%), the HSD test was applied at the 1% level (Gomez and Gomez, 2010).

RESULTS AND DISCUSSION

Application of gibberellin (GA_3) exerted a significant effect on the reproductive capacity and fruit quality of red dragon fruit (*Hylocereus polyrhizus*). The most pronounced responses were observed in the acceleration of flowering time, the increase in flower and fruit number, and the enhancement of fruit size, as indicated by higher fruit weight and volume. The optimal physiological response occurred at 400–600 ppm GA_3, which consistently produced superior values across most measured parameters without signs of performance decline (Table 1). These findings demonstrate that GA_3 acts as a pivotal regulator of the generative phase and the development of reproductive organs in *H. polyrhizus*.

This study does not include molecular data or measurements of gas exchange, which could provide further insights into the physiological mechanisms underlying the regulation of flowering and fruit development in red dragon fruit through GA_3 application during the off-season. However, the findings of this study have provided a clear understanding of the role of GA_3 in stimulating floral meristem differentiation and enhancing photosynthate translocation to generative organs, which are key factors in flowering and fruit development.

Despite the strong reproductive response, GA_3 did not induce significant changes in peel thickness. This indicates that the hormonal sensitivity of *H. polyrhizus* is organ-specific: the generative tissues (flower primordia and developing fruits) and pulp tissue are more responsive to GA_3 than the pericarp. This aligns with previous studies reporting that GA_3 primarily accelerates vegetative–generative transition, enhances floral differentiation, and enlarges fruit size through cell expansion and division in mesocarp tissues (Arivalagan et al., 2021; Sin et al., 2023).

A strong negative correlation between GA_3 concentration and days to first flowering (r =

Table 1. Effect of gibberellin concentration on days to first flowering, number of flowers, number of fruits, peel thickness, fruit weight, and fruit volume of red dragon fruit

Gibberellin concentration (ppm)	Days to first flowering (DAA)	Number of flowers (flowers plant^{-1})	Number of fruits (fruits plant^{-1})	Peel thickness (mm)	Fruit weight (g)	Fruit volume (ml)
0	19.33 ± 0.58 b	4.37 ± 0.15 a	4.30 ± 0.20 a	2.00 ± 0.00	414.99 ± 12.74 a	438.19 ± 17.76 a
200	14.33 ± 0.58 a	11.70 ± 0.36 b	11.40 ± 0.10 b	2.33 ± 0.58	495.03 ± 16.28 b	510.39 ± 26.50 b
400	13.67 ± 0.58 a	12.60 ± 0.46 b	12.20 ± 0.50 b	2.33 ± 0.58	550.27 ± 4.80 c	578.83 ± 3.82 c
600	13.33 ± 0.58 a	13.17 ± 0.90 b	12.90 ± 1.14 b	2.00 ± 0.00	504.34 ± 9.80 b	529.33 ± 10.60 b
800	13.00 ± 0.00 a	17.77 ± 0.40 c	17.53 ± 0.61 c	2.00 ± 0.00	496.60 ± 2.99 b	524.98 ± 6.30 b
HSD 5%	1.59	1.60	1.79	ns	32.04	40.32

Note: Numbers followed by the same letter within the same column are not significantly different according to the HSD test at the 5% level; the symbol "±" represents the standard deviation (SD) of the data; DAA = days after application; ns = non-significant.

–0.81*) indicates a clear acceleration of floral initiation with increasing GA_3 levels. Jiang et al. (2012) similarly found that GA_3 induces off-season pitaya flowering under short-day conditions by compensating for insufficient photoperiodic signals. Physiologically, GA_3 enhances the expression of flowering-related genes such as *FLOWERING LOCUS T* (FT) and *LEAFY*, while reducing DELLA protein accumulation that inhibits the vegetative-to-reproductive transition (Wang et al., 2024). Considering that pitaya is a long-day plant requiring >12 hours of light for natural floral induction, exogenous GA_3 functions as an alternative environmental cue under tropical conditions where day length is relatively constant (Khaimov and Mizrahi, 2006). Several studies have also documented a synergistic effect between GA_3 and supplementary lighting (night-breaking), enabling extended reproductive windows and improved synchronization of flowering (Xiong et al., 2020; Azam et al., 2021).

The strong positive correlations between GA_3 concentration, flower number (r = 0.92*), and fruit number (r = 0.92*), along with the nearly perfect relationship between flowers and fruits (r = 1.00*), indicate high efficiency in fruit set. These results support findings by Jadhav et al. (2025), who reported that hormonal regulation in *Selenicereus undatus* prolongs the flowering phase and increases fruit set via improved photosynthesis and assimilate translocation. Regression analysis (Figure 1) revealed a linear increase in reproductive output up to 600 ppm GA_3, followed by a decline at 800 ppm, suggesting a physiological saturation point likely associated with receptor saturation or negative feedback regulation. Thus, concentrations of 400–600 ppm may be considered the optimal physiological window to stimulate reproductive activity without disrupting metabolic balance. Dose-dependent responses similar to this pattern have been widely observed, whereby excessive GA_3 may reduce yield due to hormonal feedback inhibition or competition between vegetative and

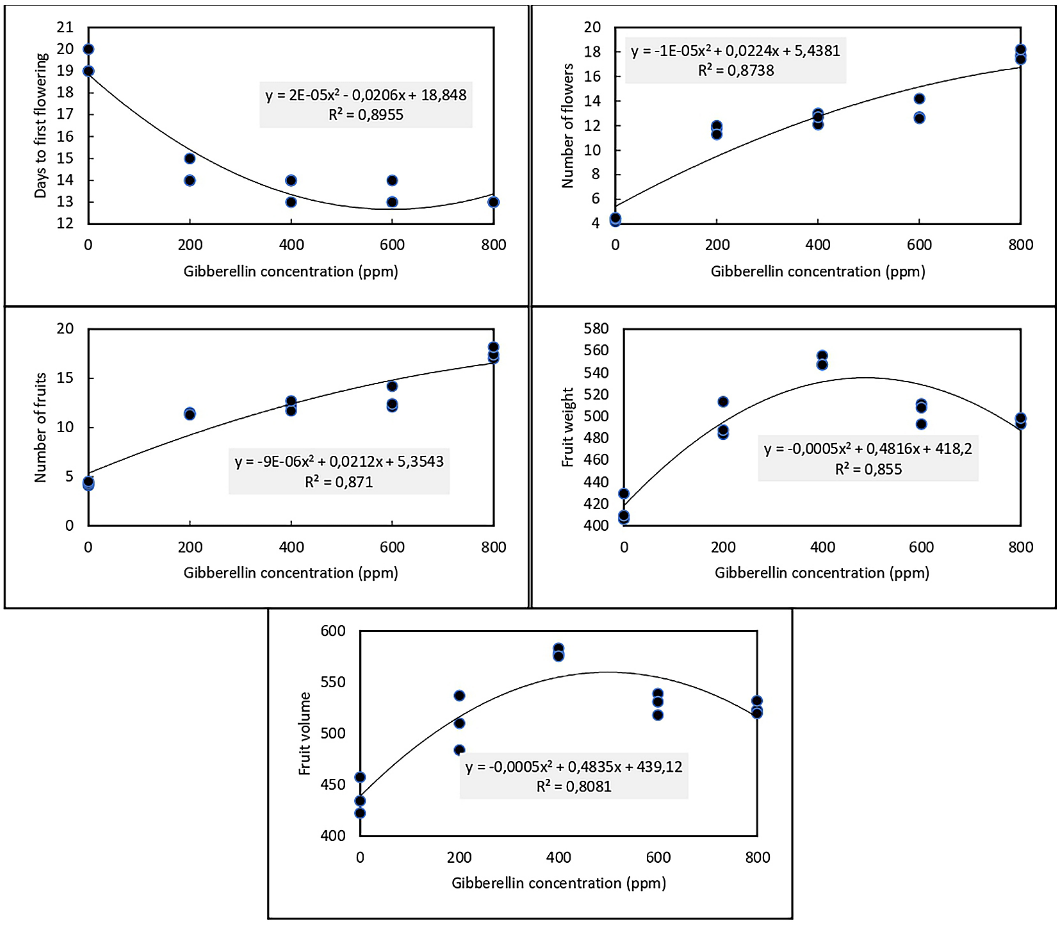

Figure 1. Regression between gibberellin concentration and days to first flowering, number of flowers, number of fruits, fruit weight, and fruit volume of red dragon fruit

generative sinks (Sin et al., 2023; Chen et al., 2023). Comparable findings in *H. undatus* show that moderate doses of GA_3 or CPPU enhance productivity, whereas excessive doses reduce fruit set (Nerd et al., 2002; Raveh et al., 1998).

GA_3 also enhanced photosynthetic capacity and carbon translocation, contributing to the significant increases in fruit weight and volume (r = 0.55* and 0.58*). According to Chen et al. (2023), GA_3 stimulates activities of invertase and sucrose synthase – key enzymes for sink strength and carbohydrate accumulation during fruit enlargement. The sigmoid regression curve observed in this study indicates maximum fruit weight at 600 ppm, with a slight decline at 800 ppm, likely due to limited assimilate supply or altered sink–source prioritization (Le Bellec et al., 2006).

In contrast, fruit quality traits such as peel thickness and soluble solids content (°Brix) did not vary significantly among treatments. This suggests that GA_3 influences morphological development more strongly than primary metabolic pathways determining sweetness. Sin et al. (2023) similarly reported that gibberellins primarily regulate cell expansion rather than sugar or organic acid composition.

Peel color assessment (Table 2) revealed a shift from strong purple-red (63A) in the control to moderate purple-red (59C) at 400–800 ppm GA_3, while anthocyanin content increased modestly from 82.72 to 83.92 mg 100 g^{-1}, although without significant differences. The positive correlation between GA_3 and anthocyanin content (r = 0.71*) reflects GA_3's ability to stimulate pigment biosynthesis via activation of the phenylpropanoid pathway, particularly chalcone synthase (CHS) and dihydroflavonol reductase (DFR), which are central to betacyanin production, the characteristic pigment of red dragon fruit (Chen et al., 2023; Tenore et al., 2012). The strong association between fruit weight and anthocyanin content (r = 0.84*) suggests that larger fruits exhibit increased secondary metabolism, supporting findings by Jiang et al. (2012) and Yadav et al. (2024) in pitaya under moderate hormonal treatments.

The Pearson correlation matrix (Table 3) further confirms strong functional linkages among flower number, fruit number, fruit weight, and fruit volume (r = 0.67–0.98*), emphasizing the interconnected nature of reproductive development and yield. In contrast, peel thickness exhibited weak correlations with most variables (r ≈ 0.2), indicating high genetic stability and low responsiveness to hormonal manipulation. The weak negative association between GA_3 and soluble solids content (r = –0.05) suggests that sucrose accumulation remains relatively unaffected by increased hormone dosage.

Taken together, the findings confirm that GA_3 application at 400–600 ppm represents the most effective physiological strategy to induce off-season flowering, enhance reproductive output, and increase fruit size without compromising fruit quality. GA_3 accelerates floral meristem differentiation, enhances photosynthetic efficiency, and optimizes carbohydrate allocation to generative organs. These results align with the conclusions of Yadav et al. (2024), who emphasized that moderate gibberellin doses provide an optimal balance between growth stimulation and metabolic stability. Consequently, optimized GA_3 application holds strong potential as a sustainable agronomic approach to support year-round production of red dragon fruit in tropical regions.

Table 2. Effect of gibberellic acid concentration on skin color, anthocyanin content, and sugar content in red dragon fruit

Gibberellin concentration (ppm)	Fruit peel color	Anthocyanin content (mg 100 g^{-1})	Soluble solids content (°Brix)
0	Strong purplish red 63A	82.72 ± 0.03	19.00 ± 1.00
200	Strong purplish red 60B	83.54 ± 0.03	17.67 ± 1.53
400	Moderate purplish red 59C	83.87 ± 0.03	18.00 ± 0.00
600	Moderate purplish red 59C	83.33 ± 0.03	18.67 ± 0.58
800	Moderate purplish red 59C	83.92 ± 0.03	18.33 ± 1.53
HSD5%		ns	ns

Note: Numbers followed by the same letter within the same column are not significantly different according to the HSD test at the 5% level; the symbol "±" represents the standard deviation (SD) of the data; DAA = days after application; ns = non-significant.

Table 3. Pearson correlation matrix describing the relationships between gibberellin concentration and morphophysiological traits of red dragon fruit

Variable	GA	DFF	NF	NFr	PT	FW	FV	SSC	AC
GA	1.00								
DFF	–0.81*	1.00							
NF	0.92*	–0.91*	1.00						
NFr	0.92*	–0.91*	1.00*	1.00					
PT	–0.14	–0.20	–0.02	–0.02	1.00				
FW	0.55*	–0.83*	0.69*	0.67*	0.22	1.00			
FV	0.58*	–0.82*	0.69*	0.67*	0.14	0.98*	1.00		
SSC	–0.05	0.20	–0.21	–0.17	0.06	–0.40	–0.38	1.00	
AC	0.71*	–0.87*	0.89*	0.88*	0.21	0.84*	0.83*	–0.33	1.00

Note: GA = gibberellin concentration; DFF = days to first flowering; NF = number of flowers; NFr = number of fruits; PT = peel thickness; FW = fruit weight; FV = fruit volume; SSC = soluble solids content (°Brix); AC = anthocyanin content. Indicates significant correlation at $p < 0.05$

CONCLUSIONS

Exogenous application of gibberellin (GA_3) significantly accelerated flowering and enhanced fruit yield of red dragon fruit under off-season conditions. GA_3 concentrations of 400–600 ppm produced the most favorable physiological responses, characterized by earlier flowering, increased flower and fruit numbers, and larger fruit weight and volume without reducing physical quality or soluble solids content. Correlative analyses further indicate that GA_3 influences not only generative development but also secondary metabolic activity, including anthocyanin biosynthesis. Overall, GA_3 serves as an effective agronomic intervention to extend the reproductive season and improve off-season productivity of *H. polyrhizus*.

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