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RESEARCH ARTICLE

Growth phenology and thermal accumulation patterns of yellow dragon fruit (*Selenicerus magalanthus* Haw.) in Indian tropics

Karunakaran Ganesan[1*], Kanupriya Chaturvedi[1*], Kundan Kishore[2], Sakthivel Thandavarajan[1], Arivalagan Manivanan[1], Prakash Chandra Tripathi[3], Ruchitha Thimmarayappa[1] & Gangadharappa Gari K Shilpa[1]

[1]ICAR-Indian Institute of Horticultural Research, Hesaraghatta Lake Post, Bengaluru 560 089, Karnataka, India
[2]ICAR- Central Horticultural Experimental Station, Bhubaneswar 751 019, Odissa, India
[3]ICAR-Subject Matter Divisions, Horticulture, New Delhi 110 012, India

*Correspondence email - kp.kanu@gmail.com, avojack2023@gmail.com

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Abstract

Dragon fruit, an exotic tropical fruit, is rapidly gaining popularity in India due to its nutritional value and increasing consumer demand. Among the various species, *Selenicereus megalanthus* Haw. (yellow dragon fruit) stands out for its unique genetic composition (tetraploid), distinctive morphological traits and superior pulp quality. However, the phenological development of *S. megalanthus* has not yet been systematically characterized. Recognizing the importance of phenological studies in optimizing crop management, the present study conducted during 2022–23 at the Central Horticultural Experiment Station (CHES), ICAR-IIHR, Hirehalli, Tumkur, Karnataka-provides a detailed description of the vegetative and reproductive growth stages of yellow dragon fruit using the extended Biologische Bundesanstalt, Bundessortenamt and Chemische Industrie (BBCH) scale. While the methodology followed established BBCH frameworks, this research expanded upon prior work by incorporating additional mesostages, capturing nuanced growth variations and refining degree-day calculations. Results revealed staggered vegetative flushes, extended reproductive bud emergence and a higher cumulative degree-day requirement (817.34 DD) for fruit maturation compared to other species previously studied. By highlighting these distinct developmental patterns, the study presents an improved phenological framework that will enhance precision in agronomic management and breeding programs. The findings offer valuable insights into optimizing crop management practices specific to *S. megalanthus* under tropical conditions.

Keywords: BBCH scale; crop management; degree days; dragon fruit; germplasm; growth stages; phenology

Introduction

Dragon fruit (*Selenicereus* spp.), botanically classified under the family Cactaceae and the order Caryophyllales, is native to tropical America. The genus *Selenicereus* is distinguished by ribbed or angled shoots and large, night-blooming flowers. Among its notable species, the yellow dragon fruit (*S. megalanthus* Haw.) is an allotetraploid (2n = 4x = 44) that originated through natural hybridization between closely related diploid taxa (1, 2). Native to South America-specifically Colombia, Peru and Ecuador-*S. megalanthus* features olive-green, three-ribbed shoots with small spines along their edges. Its large, fragrant, hermaphroditic flowers have cream-white inner petals and purple-to-yellow outer petals. These flowers bloom at night and are self-fertile, although hand pollination is commonly practiced improving fruit set (3, 4). While most commercially significant *Selenicereus* species produce fruits with red peel and white or red pulp, the yellow dragon fruit is distinct for its spined, knobby yellow peel and white sweet flesh (5–7). The fruit of *S. megalanthus* is small to medium in size (75–300 g) and is prized for its exceptional sweetness and flavour. A serving of yellow dragon fruit provides approximately 102 calories, 22 g carbohydrates (including 13 g sugars), 5 g fibre and 2 g protein. It is also a rich source of vitamin C, vitamin A, calcium, iron and magnesium (1). Despite being sensitive to heat, cold and excessive rainfall, this species has an extended fruiting season lasting up to eight months, with harvests typically occurring during winter. Yellow dragon fruit is valued both as a fresh fruit and for processing purposes.

In India, dragon fruit has recently gained increasing popularity due to its striking appearance, high nutritional value and unique flavour, making it a promising and profitable crop. Among the different species, *S. undatus* and *S. monacanthus* are primarily cultivated commercially. However, *S. megalanthus* has shown considerable potential under Indian tropical conditions owing to its sweetness, consumer appeal and market value. Currently, commercial cultivation is concentrated in Karnataka, Gujarat, Maharashtra, Andhra Pradesh and parts of Tamil Nadu. With rising domestic and export demand, the crop holds significant economic potential for small and marginal farmers due to its high return per unit area and adaptability to marginal soils.

Crop phenology, which encompasses recurring events in the plant life cycle, has generated significant scientific interest because of its sensitivity to seasonal and climatic variations that profoundly affect crop production (8). Phenological events-such as bud initiation, shoot development, flowering, fruit development and maturation-correspond to distinct developmental phases or phenophases. These are systematically categorized using the BBCH (Biologische Bundesanstalt, Bundessortenamt and Chemische Industrie) numerical scale, a standardized coding system for growth stages (9). The basic BBCH scale employs a two-digit system to represent primary and secondary growth stages, each subdivided into ten clearly distinguishable phases (10). The extended BBCH scale incorporates a third digit to account for mesostages, offering a more detailed description of crop development (11). This methodology has been extensively applied to characterize the phenological stages of various fruit crops such as mango, grape and banana (12–17).

While previous studies, have described the phenology of *S. undatus* in India, comprehensive documentation of *S. megalanthus* under Indian tropical conditions is lacking (18). The present study addresses this gap by providing a detailed characterization of *S. megalanthus* growth stages using the extended BBCH scale. Emphasis is placed on identifying variations in growth dynamics, thermal requirements and phenological stages relative to earlier studied cultivars. Accurate phenological characterization is critical for optimizing crop management, germplasm evaluation and breeding programmes (19). Understanding key phenological stages-such as bud formation and fruit development-is essential for refining agronomic practices, including nutrient management, pest and disease control and irrigation scheduling, thereby enhancing productivity and fruit quality.

Hence, the present study, conducted during 2022–23 at the CHES, Karnataka, aimed to define the phenological growth stages of yellow dragon fruit and their associated thermal requirements. By providing a comprehensive framework for characterizing vegetative and reproductive development, the findings are expected to serve as a valuable tool for optimizing crop management practices, facilitating germplasm evaluation and advancing breeding programmes, thereby supporting sustainable and enhanced productivity of this species.

Material and Methods

Plant material, experimental site, location and meteorological conditions

The phenological stages of *S. megalanthus* Haw. were examined at the IIHR Experimental Farm ((latitude: 13.34° N; longitude: 77.1° E) during 2022-23. The site is situated in a tropical wet and dry climatic zone, experiencing an annual rainfall of 630 mm and a mean annual temperature of 27.08 °C, which is slightly higher than the national average. The location records an average maximum temperature (35.4 °C) and minimum (17.21 °C), with an average relative humidity (61.5 %) while the climate is characterized by moderate rainfall during the monsoon season (June to September), hot summer (February to May) and mild winter (December to January), providing a suitable environment for studying the growth and development of yellow dragon fruit.

The soil of the experimental area is sandy loam with a pH of approximately 5.6 and organic carbon content of about 0.9 %. The study focused on the vegetative and reproductive stages of *S. megalanthus*, employing the extended BBCH scale, which uses a three-digit coding system to detail plant growth stages. Observations were conducted on two-year-old vines during the 2022 and 2023 growing periods. Weekly monitoring of shoot growth was carried out, while the progression of vegetative and reproductive buds, flowering, fruit development and maturation were recorded every two days. A total of twelve plants were randomly selected for the experiment.

Phenological stages

In the BBCH scale, the first digit represents the main growth stage, the second denotes mesostages and the third specifies secondary growth stages (9, 11). The growth cycle of yellow dragon fruit was categorized into seven primary growth stages including vegetative bud development [0], shoot development [3], development of vegetative propagated organs [4], reproductive development [5], flowering [6], fruit development [7] and fruit maturation [8]. Stages 1 (leaf development), 2 (formation of side shoots and tillering) and 9 (senescence or dormancy) were excluded as they are not applicable to dragon fruit. Being a leafless, climbing cactus, *S. megalanthus* develops photosynthetic stems instead of true leaves and hence lacks a distinct leaf development phase. Similarly, the species does not exhibit tillering or the formation of basal side shoots characteristic of monocotyledonous crops. Moreover, as a perennial succulent adapted to tropical climates, dragon fruit does not undergo true dormancy or senescence; rather, growth slows under suboptimal conditions without complete cessation of activity.

Each primary stage was further subdivided into ten secondary stages [0-9], representing either distinct qualitative phases or percentage-based growth within the main stage. Mesostages [e.g. 1, 2, 3] were used to capture vegetative and floral flushes during the growth cycle. Phenological growth stages and flower development were sequentially documented using a digital camera. To study reproductive development, four flower buds per plant were collected at different stages between July and December and their progression was photographed for detailed analysis.

Thermal timelines

The thermal time or degree days required for various phenological stages were calculated using the average number of days taken to reach a specific growth stage, the average ambient temperature and a base temperature (Tb). Given the tropical climate preference of dragon fruit, a base temperature of 10 °C was utilized to estimate the thermal time requirements for different phenological stages and expressed in degree days (18).

$$GDD = \Sigma \left((T_{max} + T_{min})/2 - Tb \right) \quad i = 1 \text{ to } n \qquad \text{(Eqn. 1)}$$

Where, GDD is the growing degree days; T_{max} is the daily maximum air temperature (°C); T_{min} is the daily minimum air temperature (°C); Tb is the base temperature (°C) and n is the number of days of specific growth stage. Weather information for the period was collected from Krishi Vigyan Kendra, Hirehalli, Tumakuru, Karnataka, India.

Results

The phenological growth stages of dragon fruit (*S. megalanthus* Haw.) span the entire growth cycle, beginning with bud development and culminating in fruit maturation. The cycle is categorized into seven primary growth stages, which include three vegetative growth stages-bud development, shoot development and the development of vegetative propagated organs and four reproductive growth stages-reproductive bud development, flowering, fruit development and fruit maturation (Table 1). These stages align with the ten principal growth stages defined in the BBCH scale. Within the primary stages, 40 secondary growth stages were described to provide a detailed understanding of the plant's development. These secondary stages were identified based on regular field observations and distinct morphological criteria recorded throughout the growth cycle. Furthermore, two mesostages were included under each principal growth stage to capture finer developmental transitions, offering a comprehensive framework for phenological characterization. The growth cycle begins with vegetative growth and shoot maturation, a process that typically spans about a year before transitioning into the reproductive phase.

Principal growth stage 0: vegetative bud development

Bud initiation in *S. megalanthus* begins in June, with peak flowering occurring in August across five cycles. During development, the areoles swell progressively and burst open as they transition through different growth stages.

First vegetative flush (mesostage 1)

011. Start of bud swelling: bud emerging from areole, fully closed by purple colored leaf primordia, surrounded by woolly trichomes.

013. End of bud swelling: bud start to enlarge; green bud scales become visible.

015. Initiation of bud elongation: in this stage scales start to separate.

017. Beginning of bud break: development of areoles and spines starts, trichomes surround areole.

019. End of bud break: areoles and soft spines become clearly visible and prominent.

Second vegetative flush (mesostage 2)

021. Beginning of bud swelling: bud emergence from the areole, with green leaf primordia, surrounded by woolly trichomes.

023. End of bud swelling: bud starts elongating; green bud scales become visible.

025. Bud elongation: scales start to separate.

027. Beginning of bud break: development of areoles and spines starts, trichomes surround areole.

029. End of bud break: areoles and soft spines become clearly visible and prominent.

Dragon fruit exhibits a cyclic flowering phase, allowing for the inclusion of additional mesostages to capture its repeated flowering cycles.

Principal growth stage 3: shoot development

After emerging, the vegetative bud develops into a columnar shoot, with the areole and spine gradually forming. In the hot and humid climate of southern India, this process takes approximately seven to eight months, with most shoots reaching maturity before March.

First vegetative flush (mesostage 1)

310. Beginning of shoot growth: the axis of the developing shoot becomes visible, and areoles begin to form.

311. Shoots at 10 % of full length: at this stage, shoots obtain light green colour, maturation of spines and prominence of ribs starts.

313. Shoots at 30 % of full length: shoots reach approximately 30 % of their final length, with areoles and spines becoming more pronounced.

Table 1. Duration and thermal time required at different phenological growth stages of dragon fruit (*Selenerius megalanthus*)

Code	Principal growth stage	Duration (days)	Thermal time (degree days)
	Vegetative bud and shoot development	**97**	**1350.82**
411	Beginning of side shoot extension	5	82.6
413	Shoots about 30 % of final length	49	683.06
415	Shoots about 50 % of final length	21	269.85
417	Shoots about 70 % of final length	9	133.695
419	Shoots about 90 % of final length	13	181.61
	Inflorescence development	**48 ± 3**	**658.25**
511	Beginning of reproductive bud swell	9	119.97
513	Beginning of bud development	17 ± 2	236.52
514	Beginning of bud elongation	6	81.42
515	Beginning of floral tube elongation	6	78.78
517	Elongation of floral tube	3	48.045
518	Elongation of floral tube in advance stage	5 ± 1	65.575
519	End of flower elongation	2	27.94
	Flowering	**7**	**98.99**
615	Pollination completion	2	28.35
617	Flower fading	3	39.585
619	End of flowering	2	31.06
	Fruit development	**48**	**684.08**
711	Fruit set	4	55.52
713	Fruits about 30 % of final size	8	111.04
715	Fruits about 50 % of final size	17	236.98
717	Fruits about 70 % of final size	6	97.05
719	Fruits about 90 % of final size	13	183.49
	Fruit maturation	**56 ± 5**	**817.34**
811	Beginning of fruit maturation	22	309.87
813	Advance colour development	3	41.79
815	Advanced maturation	7 ± 3	102.27
817	Fruit fully matures for picking	13 ± 2	195.39
819	Fruit over mature	11	168.025

315. Shoots at 50 % of full length: the shoot color transitions from light green to green and areole maturation begins.

317. Shoots at 70 % of full length: areole maturation reaches an advanced stage.

319. Shoots at 90 % or more of full length: complete maturation of areoles.

Second vegetative flush (mesostage 2)

320. Beginning of shoot growth: the axis of the developing shoot becomes visible and areoles begin to form.

321. Shoots at 10 % of full length: the shoots initially appear light green, with spine development and rib formation beginning.

323. Shoots at 30 % of full length: as they grow to about 30 % of their final length, the areoles and spines become more distinct.

325. Shoots at 50 % of full length: the shoot gradually transitions from light green to a deeper green as areole maturation begins.

327. Shoots at 70 % of full length: at an advanced stage, the areoles continue to develop.

329. Shoots at 90 % or more of full length: Areoles matures fully.

Additional mesostages: if additional growth flushes occur, corresponding mesostages can be incorporated.

Principal growth stage 4: development of vegetative propagated organ

First vegetative flush (mesostage 1)

411. Beginning of side shoot extension: the axis of the developing shoot becomes visible, with areoles and spines in the early stages of formation.

413. Shoots about 30 % of final length: areoles and spines become well-defined.

415. Shoots about 50 % of final length: the maturation process of areoles begins.

417. Shoots about 70 % of final length: the shoot transitions to a green coloration.

419. Shoots about 90 % or more of final length: areole maturation is complete and the shoots reach harvest readiness.

Second vegetative flush (mesostage2)

421. Beginning of side shoot extension: the emerging shoot axes become visible, with areoles and spines in their initial development phase.

423. Shoots about 30 % of final length: areoles and spines are clearly distinguishable.

425. Shoots about 50 % of final length: the maturation process of areoles begins.

427. Shoots about 70 % of final length: the shoot color transitions to green.

429. Shoots about 90 % or more of final length: areole maturation is complete and the shoots reach harvest readiness.

Additional mesostages: if further flushes occur, intermediate stages may be defined accordingly.

Principal growth stage 5: Inflorescence emergence or reproductive development

First reproductive flush (mesostage 1)

The emergence of flower bud will start from august; it will take 48 to 51 days from bud emergence to anthesis, initially the flower bud is in purple colour then it changes to green with purple colour edges and emergence of spines on pericarpal region.

510. Flower bud emerging from areole: light yellow bracts (scales) enclose the bud.

511. Beginning of reproductive bud swell: the buds are closed, covered by light green, purplish scales, with the stamen and pistil not yet visible.

513. Beginning of bud development: the bracts elongate and while sepals remain enclosed, the stamen and pistil become noticeable.

514. Beginning of bud elongation: sepals and styles start to elongate, the flower remains closed and petals are not visible. The pericarpal elongation also begins.

515. Beginning of floral tube elongation: sepals and style continue elongating, fully enclosing the flower and stigma maturation begins.

517. Elongation of floral tube: sepals and petals continue to elongate, with the flower still closed. Pericarpal elongation progresses and terminal bracts elongate and turn light yellow.

518. Elongation of floral tube in advance stage: sepals begin to separate, pericarpal elongation continues and anther maturation is complete.

519. End of flower elongation: sepals separate, petals become visible, forming a hollow structure. The stigma is now visible and pollen dehiscence begins.

Second reproductive flush (mesostage 2)

520. Flower bud emerging from areole: light yellow bracts (scales) enclose the emerging flower bud.

521. Beginning of reproductive bud swell: the buds are closed, covered with light green, purplish scales, with the stamen and pistil not yet visible.

523. Beginning of bud development: the bracts elongate and although sepals are still enclosed, the stamen and pistil become clearly visible.

524. Beginning of bud elongation: elongation of sepals and styles begins, the flower remains closed, petals are not yet visible and pericarpal elongation starts.

525. Beginning of floral tube elongation: sepals and styles continue elongating, fully enclosing the flower and stigma maturation begins.

527. Elongation of floral tube: sepals and petals elongate further, with the flower still closed. Pericarpal elongation continues and terminal bracts elongate and turn light yellow.

528. Elongation of floral tube in advance stage: sepals start separating, elongation of the pericarpal continues and anther maturation is complete.

529. End of flower elongation: sepals separate, petals become visible, forming a hollow structure. The stigma is now visible and pollen dehiscence begins.

Additional mesostages: if additional flushes occur, additional growth stages may be incorporated.

Principal growth stage 6: flowering

The flowers of yellow dragon fruit are distinct from those of red, pink and white-fleshed varieties. They are bell-shaped and emit a strong fragrance. The flowers typically measure 35 to 38 cm in length, with a long pericarpal region surrounded by spines. This variety is self-fertile and the process from anthesis to fruit set takes more than 48 hr.

First flowering (mesostage 1)

610. First flower opens: sepals and petals fully separate. Anther dehiscence begins and the receptive stigma is positioned well above the stamen.

611. Beginning of flowering: 10 % of flowers have opened.

612. About 20 % of flowers open: 20 % of flowers have opened.

615. Pollination completed: flowers begin to droop and sepals and petals start to close.

617. Flower fading: the flower closes and the sepals, petals and stigma begin to fade.

619. End of flowering: fruit set occurs and sepals, petals and stigma begin to dry out.

Second flowering (Mesostage 2)

620. First flower opens: sepals and petals fully separate, anther dehiscence starts and the stigma is positioned well above the stamen.

621. Beginning of flowering: 10 % of flowers open.

622. About 20 % of flowers open: 20 % of flowers open.

625. Pollination completed: flowers droop; sepals and petals begin to close.

627. Flower fading: the flower closes and sepals, petals and stigma begin to fade.

629. End of flowering: fruit set occurs and sepals, petals and stigma start to dry.

Additional flowering phases: additional mesostages can be included in case of further flushes of flowering.

Principal growth stage 7: fruit development

Yellow dragon fruits are distinct due to their unique external appearance, with a characteristic color and spines on the exocarp region, lacking bracts. The spines or thorns are actually modified bracts in yellow pitaya. Fruiting begins in September and fruit set occurs within 4 days after flowering. Successful pollination promotes fruit growth. The flower naturally withers and falls off as fruit development begins.

First fruiting (mesostage 1)

711. Fruit set: floral parts dry, with the flower still attached to the pericarpal region and embryo development begins.

713. Fruits at 30 % of final size: pericarpal growth begins, endocarp starts developing and seed formation begins.

715. Fruits at 50 % of final size: endocarp development continues, occupying about half of the pericarpal region and seed maturation begins.

717. Fruits at 70 % of final size: fruits reach 70 % of their final size.

719. Fruits at 90 % or more of final size: fruits reach 90 % or more of their final size.

Second fruiting (mesostage 2)

721. Fruit set: floral parts dry, with the flower still attached to the pericarpal region and embryo development begins.

723. Fruits at 30 % of final size: pericarpal growth begins, endocarp starts developing and seed formation begins.

725. Fruits at 50 % of final size: endocarp development continues, occupying about half of the pericarpal region and seed maturation begins.

727. Fruits at 70 % of final size: fruits reach 70 % of their final size.

729. Fruits at 90 % or more of final size: fruits reach 90 % or more of their final size.

Additional mesostages: in the case of additional fruiting flushes, new mesostages can be incorporated. All flowers of *S. megalanthus* reliably set fruit, indicating efficient pollination by nocturnal pollinators. Similar to the prolonged flowering period, the fruits also take a significant amount of time to mature, generally requiring 13–14 weeks to fully develop.

Principal growth stage 8: fruit maturity

Yellow dragon fruit takes approximately 87 to 92 days from anthesis to reach full fruit maturity. Once ready for harvest, the fruit will detach easily. The pulp is white with a slightly transparent appearance and the seeds are larger and crunchier than those of other *Hylocereus* spp. The average TSS score of the fruit measured 20 ^{o}Brix across various developmental stages and the taste is generally sweet and pleasant (Fig. 1).

Fruit maturity at first fruiting (mesostage 1)

811. Beginning of fruit maturation: the base of the fruit begins to change color to yellow and the spines remain hard.

813. Advanced color development: the fruit's exocarp turns light yellow and the base of the spines begins to soften.

815. Advanced maturation: the fruit skin turns yellow, while the parenchymatous mesocarp appears white, although the pulp is not fully developed.

817. Fruit fully mature for harvest: the color turns yellow, the pulp develops fully, attaining a transparent white color with the right consistency and flavor.

819. Over mature fruit: the spines begin to fade naturally and the pulp becomes sticky, with a rotting smell.

Thermal time requirement

Thermal time (TM) is a key concept used to connect temperature with the physiological growth of plant parts, including fruits. It is quantified in growing degree days (GDD), which represent the total heat units accumulated by a crop during its developmental stages. The duration and temperature requirements vary across the different phenophases of dragon fruit (Fig. 2). The thermal time requirement for both primary and secondary growth stages is given in Table 1. The lowest thermal time was recorded during the initiation of floral elongation (27.94 DD), followed by pollination phase (28.35 DD) and end of flowering (31.06 DD). In contrast, the beginning of fruit maturation required the highest thermal time (683.06 DD), indicating a slower rate of fruit development. The data also highlighted that a larger number of degree days were needed for the initiation of fruit maturation.

Discussion

During the vegetative stage, both primary and secondary shoots develop. Primary shoots establish the structural framework of the plant, while secondary shoots are mainly used for propagation (18). Pruning these side shoots at the proper maturity stage is crucial for optimal fruit production. It has been reported that post-harvest pruning encourages the growth of vegetative buds and aids in expanding cultivation areas (20). Shoots grow in segmented phases,

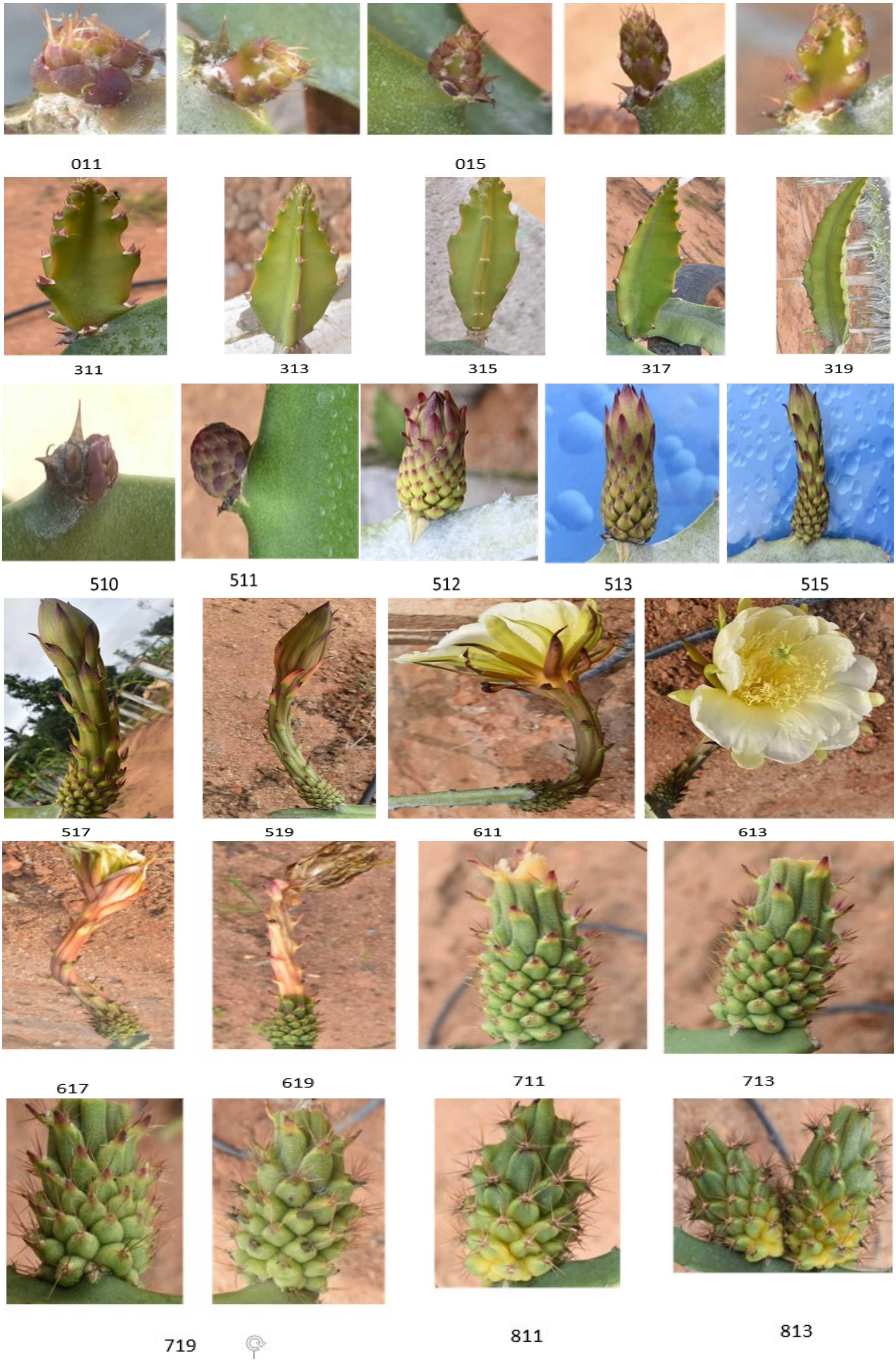
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Fig. 1. Phenological growth stages of yellow dragon fruit (*S. megalanthus* Haw.) according to the extended BBCH scale.

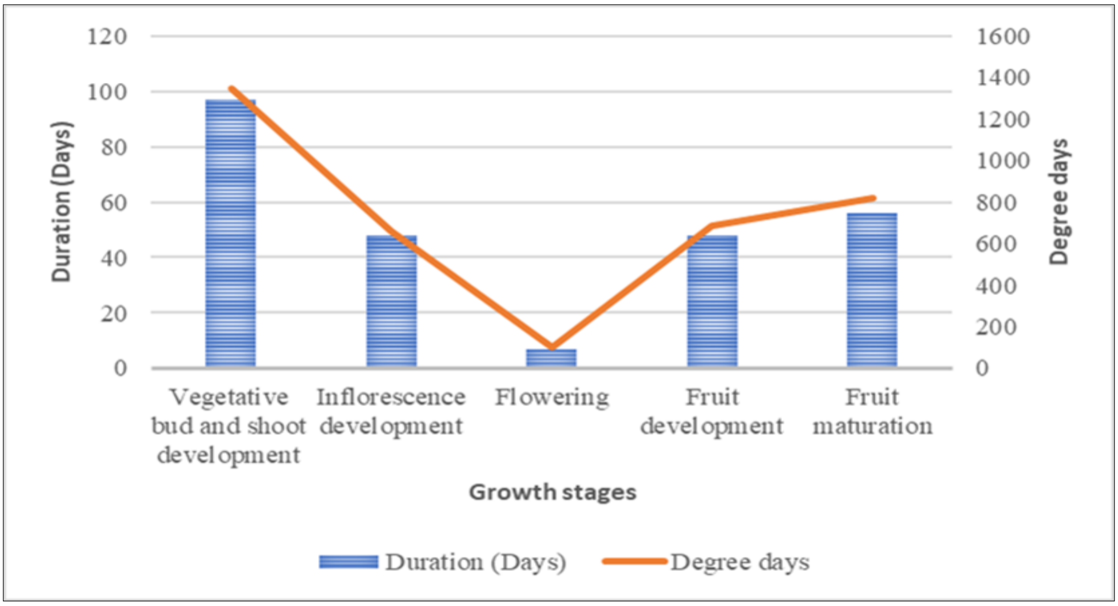

Fig. 2. Variation in thermal time under different phenological stages of dragon fruit (*Selenerius megalanthus*).

with each segment experiencing an active growth period of 3–4 months followed by a maturation phase of the same duration. Once shoot maturation is complete, the plant enters the reproductive phase, although vegetative growth continues alongside reproductive development. This overlapping growth pattern is essential for maintaining the plant's long-term productivity.

Flower bud emergence begins in August, requiring approximately 48 to 51 days from bud initiation to anthesis. Initially, the flower bud appears purple before transitioning to green with purple edges as spines develop on the pericarp region. Yellow dragon fruit undergoes multiple vegetative flushes throughout the year, with reproductive buds emerging in five to six flushes between June and December. Flowering is significantly influenced by environmental factors such as longer day lengths (≥ 13 hr), rainfall, high humidity (above 80 %) and moderate temperatures around 28 °C. Studies indicates that the ideal temperature range for flowering is 30 °C-32 °C, with relative humidity between 60 % and 80 % (21, 22). Deviations from these conditions can adversely affect bud induction. Reproductive buds form singly on the areoles of mature stems.

Bud development initially progresses slowly (stage 511) before accelerating, resulting in fully developed flowers (stage 610) within approximately seven weeks. The flowering cycle of yellow dragon fruit follows a well-defined sequence, with minimal variation in timing across stages. Notably, the completion of flower elongation (stage 519), where the flower appears as a hollow ball and the first flower opening (stage 610) occur almost simultaneously. Similarly, pollination (stage 615) and flower fading (stage 617) happen in close succession. Anthesis, characterized by the blooming of large, striking white flowers, occurs in the evening and lasts for 10–12 hr, with pollination typically taking place within this brief window. Following successful pollination, fertilization and pericarpal development begin 2–3 days later. The pollen tubes in yellow dragon fruit take approximately 48 hr to reach the base of the style, leading to successful ovule fertilization (1).

Fruit maturity is marked by a change in pericarpal color and the drooping of spines. Understanding these stages is crucial for implementing effective management practices, including pollination, nutrient application, pest control and precise harvest timing. While *Selenicereus* spp. are self-pollinating, they produce smaller fruits (80-270 g) with higher Brix levels, making them sweeter than those of *Hylocereus* spp., despite their smaller size and lower pulp content. The edible pulp of yellow dragon fruit originates from the funicle, placenta and cord, developing in tandem with the seed. Proper nutrient management is vital for maximizing yields and fruit quality, especially during both vegetative and reproductive growth stages. Given the multiple flushes of shoots and reproductive buds in yellow dragon fruit, targeted nutrient applications during these phases are particularly beneficial for boosting yields and improving fruit quality (23).

Around 79 days post-pollination, the pericarp of yellow dragon fruit begins turning yellow (stage 811), with this color change taking approximately 12 days to reach full maturity (stage 817). The timing of fruit harvest is critical for post-harvest quality. As a non-climacteric fruit, yellow dragon fruit is best consumed when harvested at the appropriate maturity stage. Premature harvesting can lead to cellular breakdown, while overripe fruit (stage 819) may have high moisture content, poor texture and diminished quality (24). For long-distance shipping, harvesting at the advanced maturation stage (stage 815) is recommended, whereas for local consumption, the fully mature stage (stage 817) is ideal.

Thermal time, representing the cumulative degree days required for completing specific growth stages, indicates that dragon fruit requires a higher degree day accumulation during fruit maturation compared to flowering. This suggests that the fruit maturation process is more energy-intensive, necessitating prolonged favorable temperature conditions, whereas flowering, being shorter and less dependent on sustained environmental conditions, requires less thermal time to reach completion.

The BBCH scale for yellow dragon fruit has been revised, differing from the previous scale used for white and red-pulped dragon fruit. The phenological growth stages, widely used in field practice and academic research, are closely linked to climatic factors. The revised BBCH scale provides more detailed and accurate descriptions of these stages, particularly emphasizing flower development, fruit growth and maturation. By incorporating climatic influences and refining stage definitions, the revised scale enhances its utility for both field applications and academic research. Furthermore, it offers broader applicability, enhancing phenological precision and relevance across various dragon fruit varieties and cultivation practices.

Conclusion

This study provides the first comprehensive phenological characterization of *S. megalanthus* under Indian tropical conditions using the extended BBCH scale. Distinct vegetative and reproductive flushes were identified, and the species was found to require a higher cumulative degree-day accumulation for fruit maturation compared to flowering, highlighting its energy-intensive developmental dynamics. By refining stage descriptions and integrating thermal requirements, the revised framework enhances precision in agronomic management, particularly for pruning, nutrient application, pollination and harvest scheduling. Beyond immediate field utility, these insights strengthen germplasm evaluation, facilitate targeted breeding strategies, and offer a valuable reference for comparative studies across different dragon fruit species, thereby supporting sustainable productivity and improved fruit quality in tropical production systems.

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Authors' contributions

KG was responsible for conceptualization, methodology and writing - review and editing. KC and KK contributed to visualization, validation and editing of the manuscript. ST and AM were involved in reviewing and editing, while PCT contributed to conceptualization and editing. RT and GGKS handled data curation and formal analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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