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Phenological Growth Stages of *Artocarpus odoratissimus* using the Extended BBCH Scale and its Applications in Determining Optimal Harvest Maturity

Isniti Richard[1], Halifah Afiza Ismail[1], Shiamala Devi Ramaiya[1]*, Gerevieve Bangi Sujang[1], Nuratika Tamimi Sheikh Mohamed[1], and Kundan Kishore[2]

[1]*Department of Crop Science, Faculty of Agricultural and Forestry Sciences, Universiti Putra Malaysia Sarawak (UPMS), Nyabau Road, 97008 Bintulu, Sarawak, Malaysia*

[2]*Central Horticultural Experiment Station (CHES), Indian Institute of Horticultural Research, Indian Council of Agricultural Research (ICAR-IIHR), 751019 Bhubaneswar, India*

ABSTRACT

Artocarpus odoratissimus, an indigenous tropical fruit native to Borneo, is highly valued by local communities for its captivating aroma and promising market potential. However, its commercialisation is hindered by limited knowledge of its phenology and inefficient harvesting practices, both of which significantly affect its shelf life. This study aims to elucidate the phenological growth stages and establish maturity indices for *A. odoratissimus* to determine the optimal harvest maturity. The study adopts the extended BBCH scale, employing a three-digit numerical system to define the phenological stages of *A. odoratissimus*, encompassing four principal growth stages: from stage 5 (reproductive part development) to stage 8 (fruit maturation). Fruit maturation progresses through three distinct phases: (i) a 40-day lag phase after anthesis (AA), (ii) a 40-day logarithmic growth phase, and (iii) a declining growth phase lasting 15 to 20 days. Detailed phenological observations indicated that optimal harvesting occurs at ~day 90 AA, when the fruits can be effectively stored, whereas harvesting at day 95 yields fruits suitable for direct consumption. These findings underscore the utility of the BBCH scale as a valuable tool for crop management, particularly for farmers. By providing a clear framework for understanding growth stages, it enables precise harvest timing, reduces fruit wastage, enhances fruit quality, and improves the marketability of *A. odoratissimus* produce.

Keywords: Artocarpus odoratissimus, BBCH scale, climacteric fruit, optimum maturity, phenology, underutilised fruit

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E-mail addresses:
isnitirichard97@gmail.com (Isniti Richard)
halifahafiza@yahoo.com (Halifah Afiza Ismail)
shiamala@upm.edu.my (Shiamala Devi Ramaiya)
gerevievebangi@gmail.com (Gerevieve Bangi Sujang)
tamimi@upm.edu.my (Nuratika Tamimi Sheikh Mohamed)
kkhort12@gmail.com (Kundan Kishore)
* Corresponding author

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INTRODUCTION

Plant phenology is the study of seasonal changes in plant life cycles, which are highly species-dependent and profoundly influence crop production dynamics (Richardson et al., 2013). Phenological events such as bud emergence, flowering, fruiting, and senescence are closely linked to specific growth stages across plant species and have critical implications for agricultural practices (Chuine & Régnière, 2017). The BBCH (*Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie*) numerical scale is widely used to delineate phenological stages in plants (Meier et al., 2009). It provides a standardised coding system for identifying and describing phenologically equivalent growth stages in both monocotyledonous and dicotyledonous plants. The scale employs a two-digit code, where the primary digits (0-9) represent the main growth stage, and the secondary digits (0-9) represent the sub-stage (Lancashire et al., 1991). The BBCH scale provides a detailed framework that enables farmers and researchers to synchronise agricultural practices with plant development, thereby improving decisions regarding planting, fertilisation, pest control, and harvesting (Meier et al., 2009). This comprehensive scale has been expanded to broad spectrum of plant species, such as dragon fruits (Chu & Chang, 2022; Kishore, 2016), java plum (Singh et al., 2021), hazelnuts (Taghavi et al., 2022), rambutan (Muhamed & Kurien, 2018), longan (Pham et al., 2015), and jackfruits (Kishore, 2018).

Artocarpus odoratissimus Blanco is an indigenous, climacteric fruit native to Southeast Asia, particularly Borneo, including Sarawak, Sabah, and Brunei. It has also been introduced to other countries, such as the Philippines, Australia, and Brazil (Bakar & Bakar, 2018). This fruit belongs to the Moraceae family, which comprises ~60 genera and over 1,400 species (Jagtap & Bapat, 2010). The most popular species from this genus include *Artocarpus heterophyllus* (Jackfruit), *Artocarpus integer* (Cempedak), and *Artocarpus altilis* (breadfruit). *Artocarpus odoratissimus,* commonly known as terap, tarap, or marang, is characterised by its spiky green exterior, which turns brownish-yellow when ripe and emits an aromatic fragrance. The juicy flesh has gained popularity in local markets and is among the most widely consumed fruits in Borneo, as reported by Karson et al. (2020). This plant holds significant economic and nutritional value, making it a highly advantageous multifunctional crop for both fruit and timber production (Zerega et al., 2005). Furthermore, *A. odoratissimus* is a rich source of essential minerals that contribute to managing conditions such as anxiety, stroke, blood pressure, and cardiovascular and renal health (Martinez & Perez, 2016).

However, *A. odoratissimus* is often classified as an underutilised fruit, primarily due to its highly perishable nature and rapid deterioration (Reddy et al., 2010). The key factors contributing to this issue include improper harvesting periods and practices. Delayed harvesting often results in fruits being picked when they are overly mature, significantly reducing their shelf life (Bakar & Bakar, 2018; Mondal et al., 2013).

The lack of information on the phenological events and standardised harvesting protocols leads to variations in maturity levels, causing the fruits to degrade more rapidly.

Understanding the phenological development of crops is crucial for optimising agricultural practices, particularly to ensure harvesting at the ideal time. This approach can help extend shelf life and maximise the value of agricultural produce. The present study aims to elucidate the phenological growth stages and establish maturity indices for *A. odoratissimus*, enabling the determination of optimal harvest maturity. This study seeks to empower growers with precise crop management techniques to ensure optimal harvest timing, preserving fruit quality, and extending shelf life.

MATERIALS AND METHODS

Study Area and Sample Collection

The study was conducted at a fruit orchard in Kampung Pasir Pandak, Kuching, Sarawak (N 4˚3'29.466" and E 113˚50'39.0948"). Sampling locations were marked using a Garmin GPSMAP® 64S to obtain the GPS coordinates. Data on vegetative and reproductive phases at different developmental stages were collected from 10 to 12-year-old plants of five *A. odoratissimus* trees from January 2022 to September 2023. In 2022, the total monthly precipitation ranged from 153.00 mm to 793.60 mm, and temperatures ranged from 25.83 °C to 27.50 °C. In 2023, the total monthly precipitation ranged from 164.80 mm to 817.40 mm, with temperatures ranging from 26.04 °C to 27.72 °C (Figure 1) (Kuching Meteorological Department, 2024).

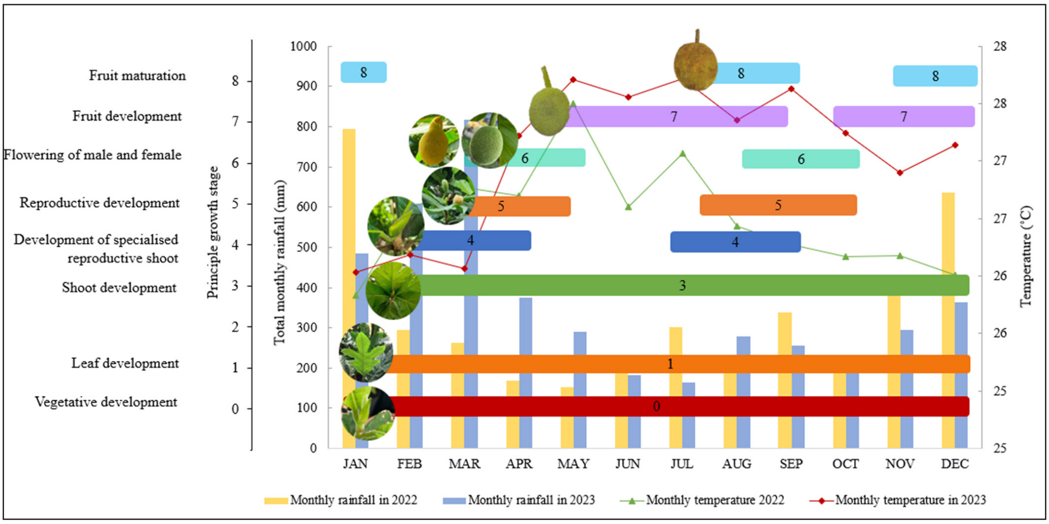


Figure 1. Principal growth stages of *Artocarpus odoratissimus* in relation to total amount of rainfall and temperature from 2022-2023 (Department of Meteorology Kuching, 2024). The bar represents the elapsed time of different growth stages

Phenological Observation

Data on various phenological stages of bud development and reproductive development were recorded at 5-day intervals. Flower buds and fruits were randomly selected across the canopy, with emphasis on mid-canopy positions, and were tagged for phenological observation. Fruit samples were subsequently collected from these tagged structures. The proposed extended BBCH scale for *A. odoratissimus* follows that of jackfruit, which is represented by four principal growth stages, starting with stage 5 (reproductive development), 6 (flowering), 7 (fruit development), and 8 (fruit maturity). Stage Principal growth stages were further divided into 10 secondary stages (0-9) corresponding to intermediate developmental stages linked to specific stages. These stages represent qualitatively different stages within a given principal growth stage. Mesostages (1, 2, 3, …) were used to define the frequency of occurrence of principal growth stages during a crop cycle. For example, code 815 represents the fruit maturation stage, indicating that the fruit is fully developed, matured, and will undergo ripening next. Besides, because *A. odoratissimus* is a monoecious plant wherein male and female inflorescences (spikes) are borne separately, stages 5 and 6 have been described separately for male and female spikes. The phenological growth stages and fruit development were sequentially characterised and photographed by the same observer throughout the study to ensure consistency.

Determination of Fruit Maturity Indices of *Artocarpus odoratissimus*

To study the maturity indexes of *A. odoratissimus*, random sampling was done to collect the fruits (8-10 fruits) at Stage 8 (fruit maturation) with five maturity stages including 811 Beginning of fruit maturation (80-85 days AA), 815 Advanced fruit maturation (90-94 days AA), 817 Fruit fully mature for picking (95-99 days AA), and 819 Fruit over mature (100-105 days AA). The collected fruit samples were immediately cleaned and analysed to determine general properties following standard protocols.

Determination of Fruit Physicochemical Properties

Fruit mass and size were measured using an electronic balance and a measuring tape. The fruit exocarp colour was assessed based on a scale ranging from 0 to 5, representing the progression from dark green to deep brown (0 = dark green, 1 = light green, 2 = greenish yellow, 3 = brownish yellow, 4 = brown, 5 = deep brown), while the flesh scale also ranging from 0 to 5, representing the progression from clear white to fully brown (0 = white, 1 = slightly whitish yellow, 2 = equal white and yellow, 3 = fully yellowish, 4 = slightly brownish, 5 = fully brown).

Additionally, colour coordinates as $L^* a^* b^*$ scale system were recorded from the fruit surface using a Colour Reader CR10. The fruit's firmness was measured using a penetrometer.

Penetrometer readings were converted to newton (N) values. The total soluble solids (TSS) were assessed using a hand-held refractometer at standard temperature (20˚C), and the results were expressed in ˚Brix (method 983.17, AOAC, 2000). The pH of the fruit was determined by using a pH meter (964.24 (AOAC, 2000).

Statistical Analyses

Data for physicochemical properties were triplicated and statistically analysed using SAS 9.4 Windows software (SAS Institute Inc, Cary, USA). Means were compared using single-factor analysis of variance (ANOVA) to compare physicochemical attributes among discrete maturity stages. Post hoc Tukey's test ($p<0.05$) was performed if the ANOVA result was significant.

RESULTS AND DISCUSSION

Phenological Event of *Artocarpus odoratissimus*

Phenology refers to the annual progression of biological development stages in plant species (Singh et al., 2023). The phenology of *A. odoratissimus* in Sarawak shows a remarkable cycle intertwined with the region's tropical climate. The success of this plant is reflected in its ability to adapt to Sarawak's distinct seasons, as evidenced by abundant fruit production during its peak season. The phenological activity observed in this study is shown in Figure 1. This fruit tree displays a distinct phenological cycle, characterised by continuous vegetative growth throughout the year, as the climatic conditions consistently support year-round development. Major flowering was recorded from March to May and from August to October, coinciding with lower to moderate rainfall in 2022, ranging from 153.00 mm to 338.80 mm and from 218.80 mm to 374.00 mm, respectively. However, in March 2023, an exceptionally high rainfall of 817.40 mm was recorded, which impacted the flowering process. The temperature ranged from 26.17 °C to 27.50 °C in 2022, and from 26.06 °C to 27.7 °C in 2023.

The *A. odoratissimus* fruiting season in Sarawak occurs twice a year, with the major season from June to August, while the minor season is from November to January. From June to August, the region experiences lower to moderate rainfall, ranging from 164.80 mm to 302.80 mm, with temperatures ranging from 26.43 °C to 27.72 °C, in both 2022 and 2023. In contrast, higher rainfall was recorded during the fruiting season from November to January, ranging from 294.40 mm to 793.60 mm, while temperature ranged from 26.01 °C to 27.14 °C in both years. In the Philippines, the fruiting season is from May to July in Luzon and from August to December in Mindanao. The flowering and fruiting in Borneo indicate that the fruit ripens between October and January (Bakar & Bakar, 2018). In Northern Queensland, Australia, the fruit was harvested over two months, peaking in February, following flowering in October to November. Yang et al. (2018) emphasised that climate temperature and soil moisture are key determinants of plant growth, affecting photosynthesis, flowering, and fruit ripening. Temperatures in the range observed in this study are ideal for promoting rapid growth and high yields in tropical fruit species. Moore et al. (2015) highlighted the influence of precipitation on phenology and productivity, demonstrating that seasonal variation in rainfall patterns can shape the timing of growth, overall productivity, and the composition of plant communities.

Phenology of *Artocarpus odoratissimus* based on the Extended BBCH Scale

The extended BBCH scale provides a detailed overview of the various phenological growth stages of *A. odoratissimus*. The phenological growth stages of *A. odoratissimus* outline its annual developmental process, beginning with bud development and culminating in fruit maturation (Table 1). In this study, the principal growth stages were categorised into four stages: stage 5 (reproductive development), stage 6 (flowering), stage 7 (fruit development), and stage 8 (fruit maturity). Based on the observation, *A. odoratissimus* exhibits continuous vegetative growth throughout the year as its vegetative buds develop in multiple flushes. These buds go through various developmental phases before finally transforming into leaves. As an evergreen plant, it produces vegetative shoots year-round, though vegetative growth slows during flowering and fruiting phases (Kishore, 2018). Hence, studies by Ador et al. (2024) reported that the flowering pattern and yield sometimes exhibit inconsistencies, and, according to Noor Camellia et al. (2012), this was due to weather conditions during bud differentiation affecting flower formation.

The initial reproductive phase of *A. odoratissimus* was dominated by the male phase, similar to other *Artocarpus* species, such as *A. heterophyllus* (Kishore, 2018). This male dominance ensures an abundant pollen availability when the female flowers are ready for fertilisation. The male spikes are densely covered with numerous fertile and sterile staminate flowers, with each stamen featuring an anther supported by a filament. Pollen dehiscence signifies the maturity of the male spike and the end of the male phase, which was followed by spike decay. This male phase cycle typically lasts 3 to 5 weeks.

In contrast, the female spikes emerge later on the bearing shoots. These spikes are usually smaller, rounder, and less conspicuous than the male flowers. The light green female flowers typically have thicker peduncles and bear numerous small, single flowers, each consisting of an ovary, style, and stigma. During development, the stigma emerges across the surface of the spikes and is sticky to capture pollen grains. The production of scent during spike maturation may facilitate insect attraction, thereby influencing phenological timing and maturity indices via pollination (Kishore et al., 2023). Upon successful pollination, the ovary begins to swell and develop into a syncarp.

The syncarp comprises multiple individual drupelets, each containing a seed surrounded by fleshy pulp. The female phase is completed in about 3-6 weeks.

Artocarpus odoratissimus fruits are syncarps composed of individual fertilised ovaries (achenes). Each achene develops into a bulb with a fleshy aril enclosing the ovary and a seed. The outer surface of the syncarp is covered with closely packed hairy protrusions that become more spaced out as it matures. The development of *A. odoratissimus* fruits follows a sigmoidal growth curve, characterised by an initial slow growth phase (lag phase), followed by a period of rapid exponential growth (log phase), and concluding with a phase where growth plateaus as the fruit matures (diminishing growth phase).

Fruit Development and Maturity Indices of *Artocarpus odoratissimus*

Understanding this growth pattern is essential for effectively cultivating and timing the harvest of the fruits. The lag phase spans 40 days after flower anthesis, followed by a 40-day log phase. During maturation, the fruit undergoes a period of diminishing growth lasting ~20 days (Figure 1). Fruit maturation begins after the completion of fruit development, marked by external and physical changes such as fruit and peduncle colouration, aroma emission, spacing of hairy protrusions, and reduced or absent latex production from the fruit. Fruit ripening takes 15 to 20 days. Once the fruit reaches its optimal harvesting period,

Table 1
The description of the phenological growth stages of Artocarpus odoratissimus *based on the extended BBCH scale*

Stage	BBCH Code	Description	Growth Stages	BBCH Code	Description	Growth Stages
5	**Development of male (A) and female (B) reproductive buds**					
	513A	Beginning of bud development (male)		513B	Beginning of bud development (female)	
	519A	Bract separation and male spike visible		519B	Bract separation and female spike visible	

Table 1 (*continued*)

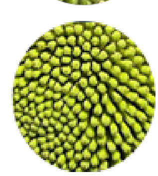
Stage	BBCH Code	Description	Growth Stages	BBCH Code	Description	Growth Stages
6	**Flowering of male (A) and female (B) (30 days)**					
	610A	Beginning of male spike developing		611A	Beginning of male spike maturation	
	615A	Pollen dehiscence started		619A	Beginning of spike decay	
	610B	Beginning of female spike developing		611B	Beginning of female spike maturation	
	613B	Advanced maturation of female spike		615B	Spike at peak stigma receptivity stage	
	619B	Fruit set				
7	**Fruit development (~70 days)**					
	710	Syncarp begins to swell		711	Syncarp growing	
	713	30% of final fruit size		715	50% of final fruit size	
	717	70% of final fruit size				

Table 1 (*continued*)

Stage	BBCH Code	Description	Growth Stages	BBCH Code	Description	Growth Stages
8	**Fruit maturation (~15-20 days)**					
	811	Beginning of fruit maturation		815	Advanced fruit maturation	 
	817	Fruit fully mature for picking		819	Fruit over mature	

it tends to become overripe if not consumed or processed immediately. The findings indicate that *A. odoratissimus* fruit reaches full developmental growth around 70 days after anthesis (AA). The fruit begins to mature at approximately 80 days AA and reaches full ripeness by around 95 days AA. However, fruits harvested after ~100 days AA are considered overripe.

Locals usually used several observational and sensory cues to determine the maturity indexes of *Artocarpus* fruits, such as colour, texture, and aroma (Elevitch & Manner, 2006). However, due to the height of the trees, the lack of distinctive colouration in the fruit, and the uncertainty about which fruits emit the characteristic aroma of ripeness, assessing factors such as texture, aroma, and external colouration is challenging, and the fruit may not exhibit clear visual cues of ripeness. To determine the appropriate maturation stage and harvesting time of *A. odoratissimus*, data on the general properties of the fruits were examined in detail in this study.

The fruit develops on day 10 AA of the flower. During the initial stage, there is rapid expansion in both fruit size and weight, primarily driven by rapid cell differentiation and enlargement. However, as the fruit progresses towards maturity, around day 80 AA, the growth rate gradually slows. At this stage, the fruit shifts its focus to maturation and ripening. The development of the pulp and seeds also occurred during this period, significantly contributing to the fruit's overall weight gain during ripening.

The findings revealed that *A. odoratissimus* fruits typically take 90 to 95 days after anthesis to reach full ripeness. This duration is similar to that of breadfruit and jackfruit, which typically require 98 and 100 days, respectively, to ripen fully (Carrington et al., 2011; Saha et al., 2016). It is noteworthy that fruit maturity is influenced by a combination of factors, including genetic makeup, the physiological condition of the specific crop, and environmental conditions (Bekele, 2018). These elements collectively play a crucial role in determining the timeline for fruit maturation. Figure 2 illustrates the developmental stages of *A. odoratissimus* fruit.

Three fruiting stages of *A. odoratissimus* have been identified in the present study: stage 1: fruit initiation, stage 2: fruit expansion and maturation, and stage 3: ripening. During stage 1, fruit initiation begins at the fruit set, marked by rapid cell division and expansion, resulting in considerable growth in length and diameter between days 10 and 20 AA. Stage 2 is known as fruit expansion and maturation. This growth continues until reaching maximum dimensions. By 60 days AA, the fruit's weight increases rapidly, reaching half its final weight by 70 days AA. During this stage, the arils expand, forming the edible flesh enveloping the seeds.

The clustered arrangement of arils within the fruit contributes significantly to its overall appearance and texture. The third stage, ripening, involves the softening and colouration of the fruit, along with the accumulation of soluble solids and acids. The flesh attains its maximum size and weight during this phase. Initially green, the fruit turns yellow or brownish-yellow as it ripens, accompanied by softening of the outer skin. Moreover, protuberances become more pronounced during ripening, while the fruit emits a sweet, fragrant aroma that intensifies with maturity. Ripening increases sugar content, resulting in a

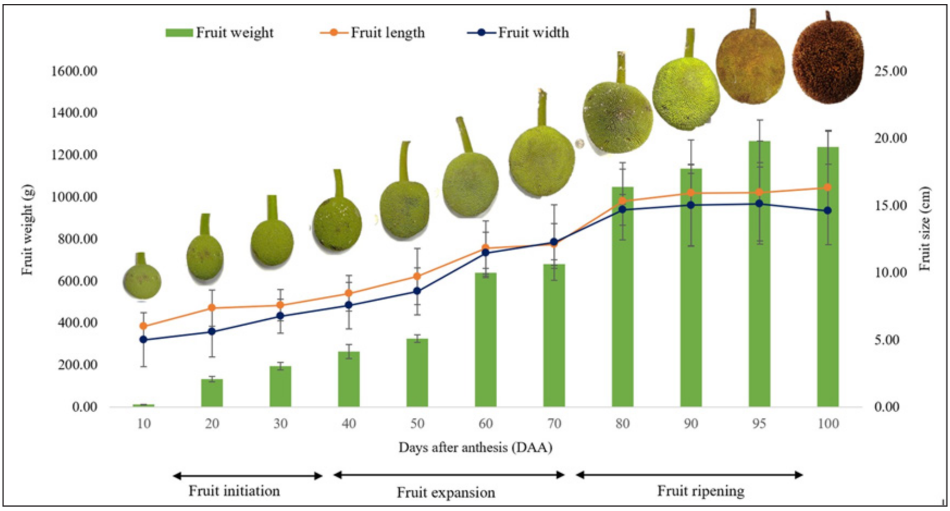


Figure 2. Fruit development of *Artocarpus odoratissimus* based on weight, length, and width

sweeter taste, and the flesh softens and becomes juicier, thereby enhancing its appeal. These collective transformations characterise ripe fruit, making it palatable and enjoyable to eat. Identifying the optimal harvesting stage is crucial for *Artocarpus* fruit. Typically harvested manually, it falls on the farmer to determine when the fruit has reached the appropriate level of maturity for harvest. The maturity of harvested produce significantly influences its shelf life and quality during storage, transportation, and marketing (Budhathoki et al., 2022). Thus, having a comprehensive understanding of maturity and employing reliable measurement techniques is imperative for *A. odoratissimus*. Ideally, the maturity index should be non-destructive and based on factual criteria rather than arbitrary standards, providing accurate insights into the commodity's quality and postharvest longevity (Reid & Jiang 2012). This holistic approach ensures that the harvested fruit meets quality standards and maintains its appeal throughout the supply chain. To determine the optimal harvest stage, maturity indices should be non-destructive and objective and should directly contribute to the quality of the commodity and its post-harvest shelf life (Reid & Jiang 2012). Data on the chemical properties of *A. odoratissimus* between 80 and 100 days after anthesis (DAA), corresponding to the maturation stage (Stage 8), are presented in Table 2. The fruit's colour, firmness, °Brix, and pH values were analysed during this period. The colour of the fruit at four different maturity stages was measured using L^* (lightness), a^* (redness), and b^* (yellowness) values. The L^* significantly differed across the stages ($p<0.05$), ranging from 42.93±2.58 at the immature stage to 24.20±2.79 at the overripe stage, decreasing as the fruit matured. The a^* value also showed a declining trend, ranging from -0.90±1.57 in immature fruits to 6.50±0.53 in fully ripened fruits. Conversely, the b^* value increased as the fruit matured, ranging from 17.80±1.47 in immature fruits to 27.77±2.03 in ripened fruits. Visual colour observations revealed that fruits harvested at 80 DAA (immature stage) were light green. At the mature stage (90 DAA), the fruit turned greenish yellow. By the ripened stage, the fruit displayed a brownish yellow to brown colour, while overripe fruits appeared dark brown.

As for the flesh, the lightness (L^*) of the flesh decreased significantly from 72.78±0.83 in immature fruits to 45.47±1.04 in overripe fruits. The a^* value, indicative of redness, exhibited a slight increase from 1.37±0.30 in immature fruits to 1.57±0.15 in fully ripe fruits. Similarly, the b^* value, representing yellowness, increased from 22.03±0.87 in immature fruits to 27.03±0.85 in ripened fruits. Visual colour observations indicated that fruits harvested at 80 days after anthesis (DAA), corresponding to the immature stage, exhibited a clear white appearance. At the mature stage (90 DAA), the fruits developed a slightly whitish yellow. During the ripened stage, the colouration transitioned to a balanced mix of white and yellow, eventually becoming fully yellowish. Overripe fruits displayed a progression from a slightly brownish tint to a fully brown colouration.

Table 2
Physicochemical properties of Artocarpus odoratissimus *fruit based on different stages of maturity*

Variables	Day 80 AA (Immature)	Day 90 AA (Mature)	Day 95 AA (Fully ripen)	Day 100 AA (Over-ripen)
Peel				
L*	42.93±2.58[a] (40.60-45.70)	32.43±3.57[b] (29.80-36.50)	27.75±0.93[bc] (26.70-28.40)	24.20±2.79[c] (21.00-26.10)
a*	-0.90±1.57[c] (0.80-(-2.30))	1.60±0.20[bc] (1.40-1.80)	3.50±0.56[b] (3.00-4.20)	6.50±0.53[a] (5.90-6.80)
b*	17.80±1.47[c] (16.50-19.40)	21.40±0.95[bc] (20.30-22.00)	23.90±1.47[ab] (22.30-25.20)	27.77±2.03[a] (25.50-29.40)
Visual	Score 1 Light green	Score 2 Greenish yellow	Score 3-4 Brownish yellow to brown	Score 5 Dark brown
Flesh				
*L**	72.78±0.83[a] (71.70-74.40)	63.30±1.04[b] (61.40-65.00)	56.63±0.84[c] (55.10-58.00)	45.47±1.04[d] (43.70-47.30)
a*	1.37±0.30[ab] (0.80-1.80)	1.03±0.23[b] (0.60-1.40)	1.93±0.09[a] (2.10-1.80)	1.57±0.15[ab] (1.80-1.30)
b*	22.03±0.87[b] (20.80-23.70)	26.47±0.59[a] (25.30-27.20)	26.30±0.60[a] (25.10-27.00)	27.03±0.85[a] (25.90-28.70)
Visual	Score 0 White	Score 1 Slightly whitish yellow	Score 2-3 Equal white yellow to Fully yellowish	Score 4-5 Slightly brownish to fully brown
Firmness (N)	12.10±0.10[a] (11.20-11.60)	6.90±0.10[b] (6.80-7.00)	4.00±0.10[c] (3.90-4.10)	0.90±0.10[d] (0.80-1.00)
Total soluble solid (°Brix)	13.20±0.26[c] (13.00-13.80)	17.60±0.30[b] (17.30-17.90)	24.03±0.15[a] (23.90-24.20)	24.50±0.10[a] (24.20-24.60)
pH	4.33±0.06[c] (4.60-4.70)	4.97±0.06[b] (4.90-5.00)	5.33±0.12[a] (5.20-5.40)	4.40±0.10[c] (4.40-4.60)

Note. Different superscript alphabet in the same row indicates differences at $p<0.05$ (ANOVA, Tukey's test). Values are given as means±standard deviation, and values in parentheses are the range

For the fruit firmness, on day 80, *A. odoratissimus* was recorded at 12.10±0.10 N. By day 90, as the fruit neared ripeness, firmness decreased to 5.90±0.10 N and further declined to 4.00±0.10 N by day 95, indicating full ripeness. By day 100, firmness dropped sharply to 0.90±0.10 N, signalling over-ripeness. This pattern aligns with findings from a study on *A. heterophyllus* by Ranasinghe and Marapana (2019). According to a study by Ranasinghe and Marapana (2019), the firmness of *A. heterophyllus* gradually decreases as it approaches ripeness, with a more rapid decline during ripening and over-ripening stages.

Table 3 presents the proposed maturity-based phenological framework that supports diversified utilisation pathways for *A. odoratissimus* fruit. Harvesting before 80 days after anthesis (AA) was not recommended due to the presence of densely packed hairy protuberances, incomplete flesh and seed development, and excessive latex production. *Artocarpus odoratissimus* fruits harvested at day 80 were considered suitable for cooking. Additionally, fruits at day 90 AA can be harvested and stored at room temperature to ripen, as this fruit is known to be climacteric (Ismail et al., 2023). Meanwhile, fruits harvested on day 95 AA are preferred for fresh consumption, as they are naturally ripened and sweeter compared to those harvested on day 90. However, by day 100, the fruits are considered overripe, with a darkened peel and an excessively soft texture. Although the flesh remains edible, it often develops a slightly tangy or unpleasant aroma, signalling the onset of over-ripeness.

Table 3
Proposed landmark phenological stages with implications for the cultural and culinary practices of Artocarpus odoratissimus *fruit based on different stages of maturity*

Landmark Phenological Stages	**Description**	**Implication for Cultural and Culinary**
Beginning of fruit maturation	Fruits harvested at day 80 after anthesis	*Artocarpus odoratissimus* fruits harvested at day 80 were considered suitable for cooking, which is a common trait observed in other Artocarpus species, such as breadnuts and jackfruit. Immature fruits from these species are often sliced and cooked as vegetables, providing a versatile and nutritious food source. Young jackfruit is popular in many cuisines, where it is cooked as a meat substitute because of its texture and nutrient density.
Advanced fruit maturation	Fruits harvested at day 90 after anthesis	Fruit at this stage is suitable to be harvested and stored at room temperature for ripening, as this fruit is known to be climacteric in nature or suitable for transport.
Fruit fully matures for picking	Fruits harvested on day 95 after anthesis	Fruits are naturally ripened and sweeter. The flesh can be eaten raw, cooked into fritters, or fermented to make organic vinegar and ice cream flavour. As for the seeds, they can be boiled or steamed and eaten as a snack. It can also be processed to make flour.
Fruit fully matures for picking	Fruits harvested on day 100 after anthesis	Overripe-darkened peel and excessively soft texture. The flesh remains edible, often develops a slightly tangy aroma, signalling the onset of over-ripeness.

Regarding TSS, reflecting mineral and sugar content in fruits and expressed in °Brix, pulp TSS increased gradually over time from 13.20±0.26 °Brix on day 80 to 24.50±0.10 °Brix on day 100, suggesting starch breakdown into sugars during later harvesting stages and rapid metabolic transformations. Similar increasing TSS trends toward maturity were noted in studies by Rana et al. (2018) and Ranasinghe and Marapana (2019) in *Artocarpus*. The pH slightly rose from 4.33±0.06 on day 80 to 5.33±0.12 on day 95, then decreased to 4.40±0.10 on day 100, indicating slight acidity in over-ripened fruits and suggesting chemical deterioration. During ripening, the slight decline in pH is attributed to the degradation of organic acids, which are either converted into sugars or utilised in respiration (Richard et al., 2025). At the overripe stage, senescence and cell wall degradation compromise membrane integrity, resulting in the release of organic acids and the formation of acidic metabolites (Kong & Singh, 2016).

Additionally, there is a slight increase in pH during the ripening process, followed by a decrease in acidity in over-ripened fruits. These findings suggest that shared physiological and biochemical processes underlie the ripening and maturation of Artocarpus species, despite differences in specific characteristics and flavours. This indicates a common ripening pattern across *Artocarpus* species, highlighting the importance of understanding these shared processes in fruit development and quality.

Limitations

Several limitations should be considered when interpreting the findings of this study. The proposed harvest windows should be applied under typical rainfall and temperature conditions, prioritising phenological staging over days after transplanting alone. The BBCH framework, when combined with key maturity indices, provides an adaptive approach to harvesting decision-making. Under unusual rainfall, the fruit development rates may alter. Therefore, confirmation of harvest readiness at BBCH stages 815-817 using instrumental measurements is recommended rather than relying solely on days after anthesis. Additionally, although the BBCH framework provides a transferable and standardised description of fruit development stages, calendar-based timing and threshold values may vary across locations; therefore, local calibration under different microclimatic conditions and management practices is recommended. Furthermore, variations in soil fertility and nutrient management may influence flowering time and fruit development rates; consequently, the phenological events reported in this study may differ across different soil and management regimes.

CONCLUSION

This study highlights the significance of understanding the phenological growth stages of *A. odoratissimus* using the extended BBCH scale, which provides a structured framework for identifying key developmental phases. Fruit maturation occurs in three distinct stages, with the optimal harvesting periods determined as day 90 after anthesis (AA) for storage and day 95 AA for immediate consumption. These findings fill a critical knowledge gap in *the phenology of A. odoratissimus*, offering practical insights to refine harvesting practices. By equipping local farmers with a valuable tool to optimise yields and sustainably manage production, this study contributes to the broader commercialisation of the fruit. Future research should explore the environmental and agronomic factors influencing its phenology and quality to further support sustainable production and market expansion.

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CONFLICTS OF INTEREST

There is no conflict of interest.

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