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Flower phenology and artificial pollination timing in two parental Excelsa coffee (*Coffea liberica* var. *dewevrei*)

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Abstract. *Najib GA, Mustofa, Maxiselly Y, Rosniawaty S. 2026. Flower phenology and artificial pollination timing in two parental Excelsa coffee (*Coffea liberica *var.* dewevrei*). Asian J Agric 10 (1): g100142. https://doi.org/10.13057/asianjagric/ g100142.* Excelsa coffee is a cross-pollinating coffee variety whose reproductive success depends on synchronization between flower phenology and pollination timing. However, information on flower development and artificial pollination timing in Excelsa coffee remains limited. This exploratory descriptive field study aimed to determine (i) the duration required for flower buds to reach the phenologically suitable stage for pollination and (ii) the artificial pollination timing associated with more rapid progression toward early fruit development under observed conditions. Field observations were conducted at Agricultural Assembly and Modernization Agency: Industrial and Refreshing Plant, Indonesia, using two six-year-old parental of Excelsa coffee plants (n=2) that pollinated multiple times and gained 12 successful pollination flowers as the samples. Flower development was monitored from inflorescence emergence (stage 51) to early fruit development (stage 71) following the BBCH scale. Parameters observed included flower bud number, flower bud length, duration to the phenologically suitable stage, and time from pollination to initial fruit development. Artificial pollination was performed at 05:00, 06:00, 07:00, and 08:00 AM, with three pollinated flowers per treatment. Data were analyzed descriptively using means, standard deviations, and population variance, and thermal accumulation was assessed using Growing Degree Days (GDD). Results showed that flower buds required approximately 25-30 days to reach the phenologically suitable stage for pollination. 70% of buds reached BBCH stage 58 on day 25, with a mean bud length of 8.03 mm, while first flowering (BBCH 60) occurred around day 30. Flower bud length exhibited greater variability during early development and became more uniform toward later stages. Following artificial pollination, all treatments reached BBCH stage 70 by day 7; however, under the observed conditions, pollination at 08:00 AM was associated with faster progression to BBCH stage 71, with 66% of samples reaching this stage by day 13. These findings provide baseline phenological information and indicate a narrow temporal window suitable for artificial pollination in Excelsa coffee under the observed conditions.

Keywords: Artificial pollination, BBCH, Excelsa coffee flower development, receptive

INTRODUCTION

Coffee is an economically important plantation crop in tropical regions, with Arabica (*Coffea arabica*), Robusta (*C. canephora*), and Liberica (*C. liberica*) representing the major cultivated species (Maxiselly et al. 2023). In Indonesia, Liberica-derived coffees, including Excelsa, remain minor components of national production but are increasingly recognized for their agronomic and market potential.

As a minority coffee species, Liberica needs encouragement to develop based on its trait potency, such as productivity, as reflected in fruit size, taste, and pest resistance (Maxiselly et al. 2025). Liberica is one of the Liberoid coffees originating in Liberia and has several varieties (Davis et al. 2022). Two of these varieties, Liberica (*C. liberica* var. *liberica*) and Excelsa (*C. liberica* var. *dewevrei*), are cultivated in Indonesia (Udarno and Setiyono 2015). Excelsa has potential as a coffee variety; it has a unique fruity-tart flavor profile, lower caffeine content (around 0.9-1%), and resilience to climate change (Hariri et al. 2023).

Despite its potential, information on the reproductive biology of Excelsa remains limited compared with Arabica and Robusta. Excelsa coffee, like Liberica, is a cross-pollinator, meaning that pollen from other plants is essential for successful pollination. According to Udarno and Setiyono (2015), Excelsa coffee is a cross-pollinating plant that produces offspring that could not be genetically identical to the parent tree.

The process by which pollen is moved from the stamen to the stigma in plants, resulting in fertilization and fruit development, is known as pollination (Gómez et al. 2023). There are two types of pollination in coffee plants: self-compatible, as in Arabica coffee, and self-incompatible, as in Robusta coffee (Prado et al. 2019). A biological process known as self-incompatibility prevents self-pollination and promotes cross-pollination, thereby increasing genetic diversity (Peer and Mir 2025). Additionally, because it prevents inbreeding and increases genotypic and phenotypic variation within natural populations, cross-pollination is often more successful than self-pollination (Gómez et al. 2023). In contrast to self-pollinating species, cross-pollinating species are more tolerant of pollen deposition from other species, according to Ashman and Arceo-Gómez (2013). This framework is relevant to Excelsa coffee, which, like Liberica and in contrast to Arabica, is predominantly cross-pollinated and relies on compatible pollen transfer for successful fertilization (Udarno and Setiyono 2015). However, despite these similarities, reproductive characteristics described in Arabica and Robusta should be interpreted cautiously when applied to Excelsa, as species-specific differences in floral phenology, stigma receptivity, and pollination timing may influence reproductive success under field conditions.

Under field conditions, coffee flowers are commonly pollinated by flower-visiting animals, especially insects, which contribute to pollen transfer and fruit set (Gómez et al. 2023; Maldonado-Cepeda et al. 2024). However, in cross-pollinating coffee species, relying solely on natural pollination may not always ensure optimal fertilization success. By physically moving pollen to a receptive stigma, artificial pollination can be used in plant breeding and agriculture. Flowering in coffee is highly transient, with anthesis occurring within a short time window and stigma receptivity lasting only a limited period. According to Dani et al. (2023), anthesis in a single coffee plant can last from two to five days during a period of intensive flowering. Successful pollination depends on the delivery of a sufficient quantity of compatible pollen grains to a receptive stigma, ensuring that fertilization can proceed effectively and result in subsequent fruit development (Gallagher and Campbell 2020). Although this principle has been discussed broadly in coffee and other cross-pollinated species, the precise timing of stigma receptivity and the optimal window for artificial pollination in Excelsa coffee remain poorly documented. Likewise, detailed descriptions of flower development from inflorescence emergence to the phenologically suitable for pollination in Excelsa are still scarce. Determining the optimal timing for artificial pollination and understanding the growth of coffee flowers from the initial to phenologically suitable stage for pollination are therefore essential.

The purpose of this study is to determine the optimal time for artificial pollination, as well as the duration required for Excelsa coffee flower growth from inflorescence emergence to the receptive (flowering) phase. The *Biologische Bundesanstalt, Bundessortenamt,* and *CHemische Industrie* (BBCH) scale was used for the observations. Based on these considerations, this study tested the following hypothesis: Excelsa coffee (*C. liberica* var. *dewevrei*) flowers exhibit a narrow temporal window of stigma receptivity, such that pollination performed at the appropriate early-morning stage would result in more rapid progression to early fruit development than pollination applied outside that optimal window. The findings of this study are expected to provide a phenological reference for optimizing artificial pollination practices and to support future breeding and cultivation strategies for Excelsa coffee under field conditions.

MATERIALS AND METHODS

Study area

The research was conducted at the Balai Perakitan dan Pengujian Tanaman (BRMP) for Industrial and Refreshing Crops, Parungkuda Sub-district, Sukabumi District, West Java Province, Indonesia (-6.844107, 106.753368). The site is located at an altitude of approximately 500 meters above sea level and classified as a medium plain. The study was carried out from July 2025 to August 2025, with an average temperature of 23.8°C, relative humidity of 86.6%, and an average rainfall of 7.541 mm/day.

Materials

The plant material used was two 6-year-old Excelsa coffee plants (Accessions 1 and 2) in the productive phase based on the BRMP collection. Due to the limited availability of flowering Excelsa accessions suitable for synchronized observation at the study site, this study was designed as an exploratory descriptive assessment using two parental that pollinated multiple times. One plant was used primarily as the pollen donor, while the other served as the recipient plant for controlled hand pollination. The recipient flower that successfully pollination which is 12 flower being a sample of observation. The tools used in this study included plant labels for sample identification, vernier calipers and rulers for measuring flower bud length and developmental changes, tweezers for handling floral structures during observation and artificial pollination, and documentation equipment for capturing images of floral morphology and phenological stages throughout the observation period.

Methods

Experimental design and observations

This study was conducted as a descriptive-exploratory field observation, spatially controlled field experiment. Therefore, a plot-based spatial design was not applied. Artificial pollination was performed at 5:00, 6:00, 7:00, and 8:00 AM on flowers located on different branches, with three flowers pollinated per time treatment. Branches were selected from different positions on the experimental plants to reduce the effects of local clustering. However, these branches should be considered as observation units, not fully independent biological replicates because each sample potential has various traits. Therefore, the resulting comparisons are interpreted descriptively, not inferentially.

The following criteria were noted: (i) flower bud number (10 samples from multiple branches), (ii) flower bud length (10 samples from multiple branches), (iii) time required for flower buds to reach the phenologically suitable stage for pollination (10 samples from multiple branches), and (iv) time required after pollination to reach initial fruit development under different artificial pollination times with three pollinated flowers per treatment. Table 1 presents the average hourly temperature and relative humidity recorded over 30 days.

Artificial pollination procedure

Artificial pollination was conducted by manually transferring pollen from donor flowers to the stigma of selected flowers at a phenologically suitable stage. Pollen was collected from freshly opened Excelsa coffee flowers located on different branches of separate plants to ensure cross-pollination and to avoid self-pollination. Pollination was performed using sterilized tweezers, which were soaked in distilled water for 24 h prior to use, and the anthers were gently brushed onto the stigma surface. The suitability of flowers for pollination was determined visually based on external floral characteristics, including stigma plumpness and the presence of surface moisture. Because no biochemical or microscopic validation of stigma receptivity was performed, this assessment should be interpreted as a phenological or visual proxy rather than direct physiological confirmation of stigma receptivity. Each pollinated flower was labeled to record the exact time and date of pollination, and subsequent phenological development was monitored daily. After pollination, all unopened and unpollinated flower buds on the same branch were removed to prevent post-pollination floral bloom (Prado et al. 2018).

Flower bud measurement

Vernier calipers were used to measure the length of flower buds, with observations conducted on ten representative samples selected along the base to the tip. Measurements were taken periodically throughout the observation period to capture changes in bud development. The use of vernier calipers enabled precise quantification of flower bud length, ensuring accurate assessment of growth dynamics across developmental stages.

Phenological assessment using the BBCH scale

The *Biologische Bundesanstalt, Bundessortenamt,* and *Chemische Industrie* (BBCH) scale was applied to systematically quantify the duration required for flower buds to reach the phenologically suitable stage for pollination, as well as the time elapsed from pollination to the initiation of fruit development. Developmental stages were identified based on visible morphological characteristics. For the pollination-timing assessment, observations were conducted on three pollinated flowers per time treatment, and the resulting data were interpreted descriptively. The BBCH scale provides a standardized phenological framework that facilitates consistent identification and classification of plant growth stages based on visible morphological characteristics.

According to Arcila-Pulgarín et al. (2002), coffee plant development is classified into distinct growth stages, including germination and vegetative propagation (stage 0), leaf development on young shoots and branches (stage 1), branch formation (stage 2), branch elongation (stage 3), inflorescence emergence (stage 5), flowering (stage 6), fruit development (stage 7), fruit and seed ripening (stage 8), and senescence (stage 9).

This study specifically focused on the reproductive phase spanning from inflorescence emergence (stage 5) to the initial stages of fruit development (stage 7), as this interval encompasses critical events related to flower development, anthesis, and early fruit set (Arcila-Pulgarín et al. 2002):

Stage 5: Inflorescence emergence

51 Inflorescence buds swelling in leaf axils
53 Inflorescence buds burst and are covered by brown mucilage; no flowers are visible
57 Flowers visible, still closed and tightly joined, borne on a multiflowered inflorescence (3-4 flowers per inflorescence)
58 Flowers visible, untight, still closed, petals 4-6 mm long and green (dormant stage)
59 Flowers with elongated petals (6-10 mm long), still closed, and white in color

Stage 6: Flowering

60 First flowers open
61 10% of flowers open
63 30% of flowers open
65 50% of flowers open
67 70% of flowers open
69 90% of flowers open

Stage 7: Development of fruit

70 Fruits are visible as small yellowish berries
71 Fruit set: Beginning of berry growth; Fruits have reached 10% of its final size (pinheads)
73 Fruits are light green, and its contents are liquid and crystalline. Fruits have reached 30% of their final size (fast growth).
75 Fruits are light green and its contents are liquid and crystalline. Fruits have reached 50% of its final size
77 Fruits are light green and its contents are solid and white. Fruits have reached 70% of its final size
79 Fruits are pale green and its contents are solid and white. Physiological maturity is complete; Fruits have reached 90% of its final size

Growing Degree Days (GDD) represent the accumulated heat between phenological phases, defined by the following equation:

$$GDD = \sum_{i=1}^{n} \left(\frac{T_{max} + T_{min}}{2} - T_b \right)$$

T_{max} and T_{min} are the daily maximum and minimum air temperatures, respectively, Tb is the base temperature set at 10°C, below which coffee growth does not occur (Jaramillo-Robledo et al. 1998), and n is the number of days that elapse between two phenological phases (Salazar et al. 2019). Daily maximum and minimum air temperature (Tmax and Tmin) data for the observation period were retrieved from the NASA Prediction Of Worldwide Energy Resources (POWER) Data Access Viewer.

Table 1. Average of temperature and relative humidity for each hour

Parameter(s)	Hour (AM)			
	5.00	**6.00**	**7.00**	**8.00**
Temperature (C)	20.74	21.45	22.93	24.48
Relative Humidity (%)	96.69	95.21	90.54	83.74

Data analysis

The data obtained included minimum values, maximum values, means, standard deviations, and population variances (σ^2). Population variance is a measure of variability calculated as the square of the standard deviation (Maxiselly et al. 2024). A variance value equal to or greater than two multiplied by the standard deviation ($\sigma^2 \geq 2$.STDEV σ^2) indicates wide variability, while variability is narrow when the variance is less than two multiplied by the standard deviation ($\sigma^2 < 2$.STDEV σ^2) (Anderson and Bancroft 1952; Sihombing et al. 2022; Saadah et al. 2023; Maxiselly et al. 2024). BBCH data for each flower bud is described descriptively. Data visualization was performed using Microsoft Excel 2021.

RESULTS AND DISCUSSION

Number of flower buds

Table 2 shows a progressive increase in the number of flower buds during the observation period. During the first week, plants produced an average of 5.7 flower buds per node, ranging from 1 to 10. By the seventh week, the mean number of flower buds increased to 12.8, with a range of 2-26, indicating continued floral development as the plants approached later reproductive stages. According to Randriani and Dani (2018), coffee flowers are typically arranged in clusters of 4-6 flowers per axil, with each leaf axil producing 8-18 flowers or each node potentially producing 16-32 flowers.

According to Sihombing et al. (2022), a narrow variance is obtained from a variance value less than 2 × STDEV, which means that this trait exhibits a high degree of similarity even though it differs by a few weeks from the overall population. The variance was calculated based on 10 representative samples observed consistently across weeks to describe the dispersion in flower bud number. The variance in flower bud number increased from 3.723 in the first week to 5.550 in the seventh week, indicating greater variability among observed samples as floral initiation progressed. This pattern suggests that flower bud development was not fully synchronized during the early reproductive phase under the observed field conditions.

Flower bud length

The mean flower bud length increased from 2.443 mm in the first week (0.93-3.45 mm) to 8.82 mm in the seventh week (3.8-13.9 mm), indicating a progressive elongation during the observation period (Table 3). This range is consistent with previous reports that flower buds in the pre-anthesis stage typically reach 6-10 mm in length (Unigarro et al. 2023).

A clear increasing trend in flower bud length was observed across weeks. The average weekly growth rate, calculated as the change in mean length over time, indicates steady bud elongation throughout the developmental period. Variability in flower bud length was greater during the first week of observation because the variance exceeds twice the standard deviation ($\sigma^2 \geq 2$.STDEV σ^2) (Maxiselly et al. 2024), and became relatively more uniform toward later weeks, as reflected by the dispersion values in Table 3. This pattern suggests that early developmental stages exhibit higher heterogeneity in bud size, while later stages show more synchronized growth pattern under the observed field conditions. According to Unigarro et al. (2025), coffee flowering frequently shows asynchronous development both within a single inflorescence and among different branches of the same plant, leading to differences in anthesis timing and subsequent fruit set.

Duration to phenologically suitable stage

Based on the study's result, 70% of buds reached stage 58 (Figure 1) by day 25 of the sixth week, with an average length of 8.03 mm. According to Unigarro et al. (2023), stage 58 in coffee is described as a short quiescent or dormant phase lasting approximately three to four days before corolla opening. Although the duration in the present study was inferred from BBCH stage progression rather than measured directly. 20% of flower buds have reached stage 60 (initial flowering), 10% have reached stage 63 (30% of flowers are open), and 20% have reached stage 69 (90% of flowers are open) in the seventh week (day 30). Under the observed conditions, these results indicate that Excelsa coffee flower buds were associated with a transition to the phenologically suitable stage for artificial pollination within approximately 25-30 days after the initial visible bud stage. For contextual comparison, Arabica coffee has been reported to require approximately 120 days from flower bud initiation to anthesis, including the dormant phase (Angelo 2024). Likewise, flowering in tea (*Camellia sinensis*) has been reported to occur within 24-28 days, encompassing flower induction, initiation, and organ development (Shi et al. 2025).

The emergence of flower buds (stage 51) to the anthesis phase (stage 69) is represented by the first sigmoidal curve (Figure 2), characterized by slower initial growth of the flower buds, followed by rapid growth, and then slow growth again (Salazar et al. 2019). During the first 5-10 days, most samples remained at the early inflorescence stages (stage 51-53), indicating relatively slow initial development. Between days 10 and 25, the majority of samples progressed toward stage 57-58, reflecting a more active elongation phase during inflorescence emergence. After day 25, a rapid transition was observed in several samples, with some buds rapidly advancing from stage 58 to stages 63-69 by day 30. This pattern supports the use of BBCH stage progression as a practical phenological reference for estimating the suitable timing of artificial pollination in Excelsa coffee under the observed field conditions.

Duration from pollination to the initial fruit development phase

On the 7th day after pollination, all samples across all pollination time treatments reached stage 70, corresponding to the early phase of fruit development, characterized by the appearance of small, yellow fruits (Arcila-Pulgarín et al. 2002). No differences were observed among treatments at this stage. By day 10 after pollination, one out of three samples (33%) from the 08:00 AM pollination treatment progressed to stage 71, defined as fruit development reaching approximately 10% of its final size. At day 13, two out of three samples (66%) from the 08:00 AM treatment had reached stage 71, while samples from pollination times between 05:00 and 07:00 AM remained at stage 70. Under the observed conditions, the 08:00 AM treatment was associated with a more rapid transition to BBCH stage 71. This pattern should be interpreted cautiously because the number of samples per treatment was limited (n = 3), and no inferential statistical comparisons were performed. Therefore, these findings are considered descriptive and observational.

The research site's average temperature was 23.8°C (Figure 3), which is presented here only as environmental context. Coffee flower bud development takes place at an average annual temperature between 17 and 23°C, according to Rendón-Sáenz et al. (2025). The observed phenological progression required approximately 25 days for inflorescence emergence, 5 days for flowering, and 13 days for the transition from pollination to early fruit development (Figure 4).

Figure 1. Flower development based on the BBCH scale

Growing Degree Days (GDD) were further used to characterize heat accumulation across phenological phases from flower emergence to early fruit development (Figure 5). Excelsa coffee has a relatively high cumulative heat requirement compared with other coffee types (7715 GDD) (Salazar et al. 2019). In this study, GDD accumulation ranged from 75.14 to 213.04 during the inflorescence emergence phase (BBCH 57-59), with the greatest accumulation at BBCH 57. The flowering phase followed, and with a GDD value of just 67.65 GDD. This is in line with the statement by Salazar et al. (2019) that the heat unit requirement during the flowering phase is smaller, requiring only 29-80 GDD in each phenophase. The heat units during the fruit development phase increase again, with the highest value of 98.99 GDD at BBCH 70, indicating a need for additional heat units to facilitate fruit development. In this study, GDD was used to describe phenological heat accumulation only and was not statistically tested as a determinant of differences among pollination time treatments.

Table 2. Variance in the number of flower buds

Week	Min	Max	Mean	STDEV	σ2	2*STDEV	Note
1	1	10	5.7	3.466	3.723	6.931	Narrow
2	2	14	7.6	4.169	4.083	8.337	Narrow
3	2	15	8.0	4.595	4.287	9.189	Narrow
4	2	16	8.9	5.065	4.501	10.130	Narrow
5	2	20	10.5	6.023	4.908	12.046	Narrow
6	2	22	11.4	6.484	5.093	12.968	Narrow
7	2	26	12.8	7.700	5.550	15.400	Narrow

Note: Min: Minimum, Max: Maximum, STDEV: Standard deviation, σ2: Variance

Table 3. Variance in flower bud length

Week	Min	Max	Mean	STDEV	σ^2	2*STDEV	Note
1	0.93	3.45	2.443	0.926	1.924	1.851	Wide
2	1.71	6.33	4.481	1.698	2.606	3.395	Narrow
3	2.33	8.62	5.88	2.203	2.969	4.406	Narrow
4	3.1	11.5	6.883	2.707	3.291	5.415	Narrow
5	3.1	12.2	7.53	2.987	3.457	5.974	Narrow
6	3.4	13.5	8.03	3.098	3.520	6.195	Narrow
7	3.8	13.9	8.82	3.280	3.622	6.560	Narrow

Note: Min: Minimum, Max: Maximum, STDEV: Standard deviation, σ2: Variance

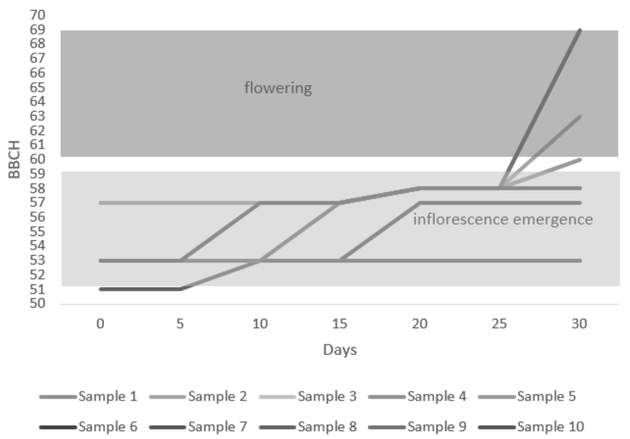

Figure 2. Development of the coffee excelsa phase, based on the BBCH Index

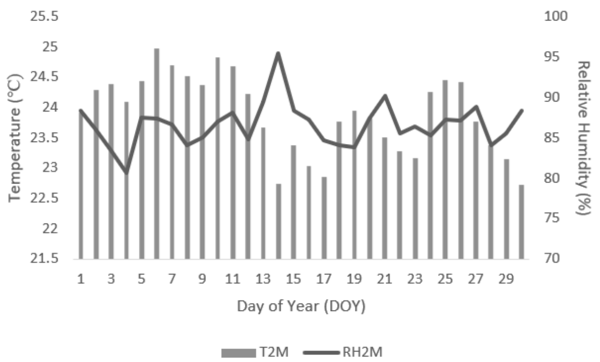

Figure 3. Daily temperature and relative humidity during observation period

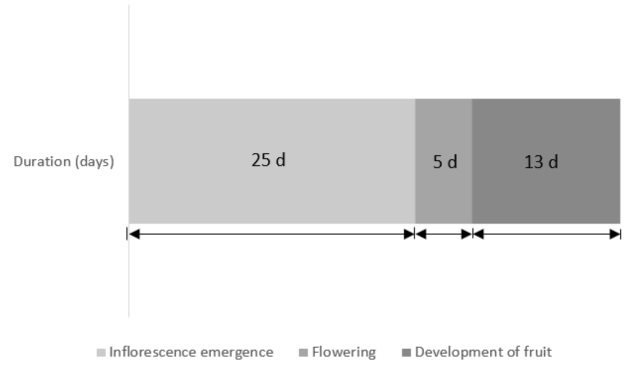

Figure 4. Duration of phenological transition phases in Excelsa coffee from inflorescence emergence to early fruit development

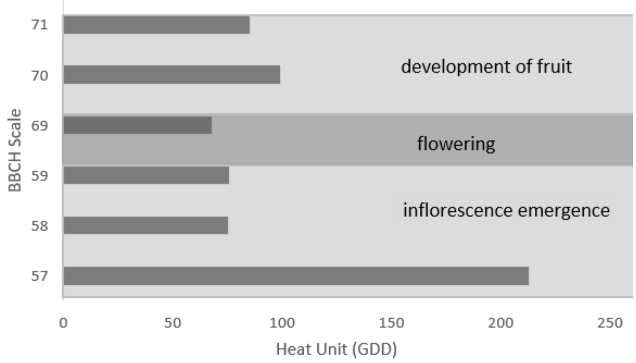

Figure 5. Accumulation of heat units (GDD) per BBCH stage from flower emergence to early fruit development

In conclusion, this study provides descriptive insights into flower bud development and early post-pollination fruit formation in coffee under the observed field conditions. Flower buds required approximately 25-30 days to reach the phenologically suitable stage for pollination phase, with 70% of buds attaining BBCH stage 58 on day 25 and exhibiting a mean bud length of 8.03 mm. First flowering (BBCH stage 60) occurred around day 30, indicating a relatively short developmental period compared with Arabica coffee. Flower bud length showed greater variability during early development (week 1) and became progressively more uniform in later stages, reflecting increasing synchronization as flowering approached. Following artificial pollination, all treatments reached BBCH stage 70 by day 7. Pollination conducted at 08:00 AM showed a descriptively faster early fruit development pattern, with 66% of pollinated flowers reaching BBCH stage 71 by day 13, whereas flowers pollinated earlier (05:00-07:00 AM) remained at BBCH stage 70 over the same period.

This study was descriptive and exploratory, with a limited number of plants and replications, and did not apply inferential statistical testing or quantify final fruit set or yield. Flower phenologically suitable stage for pollination was inferred from phenological stages rather than direct physiological measurements. Increasing sample size and replication is therefore recommended to more accurately assess the effects of pollination timing on coffee flower and fruit development. Despite these limitations, the identification of distinct temporal patterns in flower phenologically suitable stage for pollination has practical relevance for coffee cultivation, particularly for improving the precision and efficiency of artificial pollination. Future research should also account for environmental variables such as temperature, humidity, soil conditions, and light intensity, as these can affect both flower development and subsequent fruit formation. Incorporating these factors into study designs will offer a deeper understanding of coffee reproductive biology, ultimately providing solid, evidence-based guidance for improving coffee productivity and long-term crop management.

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