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Impact of climate variability on the flowering and cherry filling in robusta coffee (*Coffea canephora* Pierre) in Yangambi, Democratic Republic of the Congo

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Abstract

The Robusta coffee plant (*Coffea canephora*) is widely cultivated in humid tropical regions, but its reproductive cycle remains sensitive to climate change. In response to this observation, a study conducted in Yangambi to assess the influence of climatic conditions on the flowering and cherry filling of the Lula variety of Robusta from 2023 to 2025. A panel of 105 trees monitored monthly for presence, frequency, and intensity of flowering, as well as for the distribution of fruits by filling categories. These data's compared with monthly precipitation, temperatures, and relative humidity.

The results show an almost continuous flowering, with 72.2% of months having 100% of trees in bloom and a bimodal dynamic dominated by January-February and September-December, punctuated by local fruit drops (15.2% in August 2023 and 41.0% in April 2024). Climate shift models reveal a positive effect of two-month-delayed rainfall on the frequency and intensity of flowering, while high humidity and elevated minimum temperatures reduce the floral load. The cherry filling is optimal at the beginning of the year (71-100% of a category fruits) but drops to 0% between July and October in some years, with a significant increase in caracoli and aborted fruits.

The study indicates that the reproductive success of robusta at Yangambi depends on the intra-annual rainfall structure and the trajectory of minimum temperatures, highlighting the need to select tolerant genotypes and adjust cultivation practices in response to increased climate change.

Keywords: Flowering, climate change, rainfall, temperature, relative humidity, robusta

Introduction

The coffee tree is one of the main cash crops in many tropical regions, where it plays a significant role in the income of small producers and international trade (Bunn *et al.*, 2015) ^[6]. Among the cultivated species, *Coffea canephora* (robusta) holds an important place in hot and humid low and mid-altitude areas, due to its relative tolerance to high temperatures and its high productivity in environments where Arabica is less suitable (DaMatta & Ramalho, 2006; DaMatta *et al.*, 2007; DaMatta, 2019) ^[13, 14, 15, 16].

In Democratic Republic of the Congo, particularly in central Congolese basin, robusta represents a potential pillar for coffee revival, but this ambition faces recent significant climate change. Climate change is already evident through rising temperatures, altered rainfall patterns, and an increase in extreme events, with notable impacts on perennial crops (IPCC, 2021) ^[17].

Contrary to its image as a 'robust' plant, *C. canephora* exhibits thermal and water thresholds beyond which its physiology, flowering, and fruiting are disrupted (DaMatta, 2019; Jaramillo *et al.*, 2011; Kath *et al.*, 2020) ^[13, 15, 18, 22]. In humid tropical areas, where there is more or less marked variation between dry and wet periods, this intra-annual variability in rainfall and temperatures can alter the synchronization of flowering, the load of flowers and fruits, as well as the final seeds quality (Bunn *et al.*, 2015; Magrach *et al.*, 2020) ^[6, 23]. The flowering phenology of the coffee plant, particularly frequency, intensity, and flowering time, plays a crucial role in harvests regularity and coffee produced quality (DaMatta, 2019) ^[13, 15].

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Coffee flowering is often triggered by specific climatic sequences, such as a short period of water deficit followed by the return of rains, which synchronize flowering and influence the uniformity of cherry ripening (DaMatta *et al.*, 2019; Magrach *et al.*, 2020) [13, 15, 23].

When these sequences are disrupted (prolonged drought episodes, irregular or shifted rainfall, temperature anomalies), flowering can become spread out, the fruit set less effective, and maturation more heterogeneous, which results in potential yield losses and increased harvest and post-harvest constraints (Bunn *et al.*, 2015; DaMatta *et al.*, 2019) [6, 13, 15]. Beyond the triggering of flowering, ovary filling rate is also sensitive to the water and thermal conditions encountered during the reproductive cycle.

Rainfall deficits at the beginning of cherry development or abnormally high temperatures can reduce the ovary filling rate, increase the proportion of malformed or aborted fruits, and degrade the physiological quality of the seeds (DaMatta, 2019;

DaMatta *et al.*, 2019) [13, 15]. Despite the agronomic importance of these processes, the quantitative relationships between climate change, flowering dynamics, and ovary filling rate remain insufficiently documented for robusta in a humid tropical rainforest climate of the central Congo basin at Yangambi.

Material and Methods

Study environment

This study was conducted in Yangambi, a historic Robusta coffee-growing region, at the National Coffee Research Program site in northern Yangambi, about 100 km west from Kisangani (Tshopo Province), on the right of the Congo River in Democratic Republic of the Congo. The coordinates, recorded with a Garmin 65s GPS (global positioning system), were 00° 51'00.0" N latitude, 024° 27'49.9" E longitude, and an altitude of 458 meters. These details helped to create the map shown in figure 1.

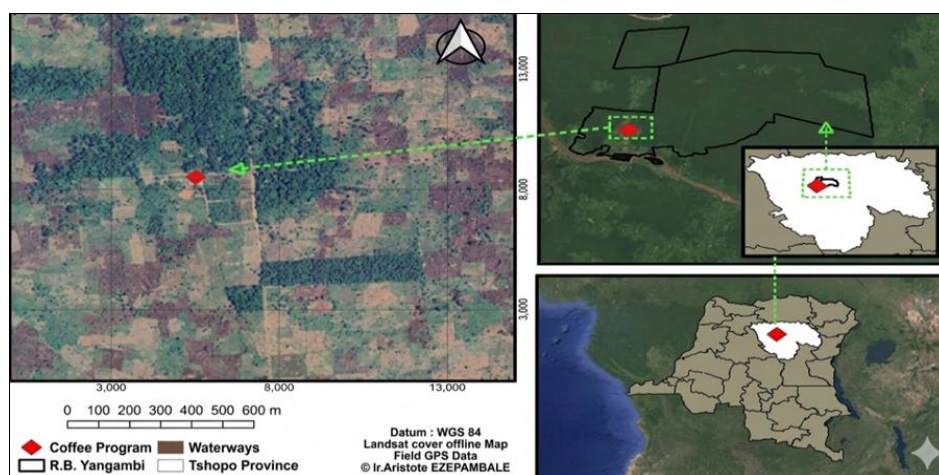


Fig 1: Yangambi Map/Coffee Program

Materials and method

Direct observation used as the primary method, with a probabilistic sampling approach based on continuous monitoring of flowering, its frequency and intensity, and mixed Robusta Lula coffee tree cherry filling rate over a period of three years (2023-2025). Lula mixed coffee tree, which included more than 263 genotypes from the National Coffee Research Program collection at Yangambi.

Collection of climatic parameters

Temperature, precipitation, and relative humidity are the main climatic parameters studied. Data collected at INERA climatological station in Yangambi, at PK 5, from daily observations. Precipitation was recorded each day and logged in a register, indicating the amount of rainfall (mm), as well as maximum and minimum temperatures and relative humidity. Cumulative totals and monthly and annual averages were calculated. These data cover the period from 2023 to 2025.

Selection of trees and sampling

Among 509 mixed Lula coffee trees recorded in the coffee program collection, 493 were selected after excluding those affected by various constraints (tight spacing, diseases, stunted plants, excessive shading) in order to better represent the potential of the material. In total, 105 trees randomly chosen as observation units, representing 21% of the population. These trees come from a coffee plantation established approximately 6 to 8 years ago.

Each selected tree received a unique code (tree number) to enable ongoing monitoring over three years. On each tree, four branches were chosen at three positions within the canopy (bottom, middle, top) and permanently marked with plastic tags to facilitate flowering events observations.

Followed by flowering and fruiting

Regular monitoring carried out on the selected trees throughout the production cycles. Observations conducted weekly, with increased monitoring during critical periods (the end of the dry season, the start of the rains, and phases of mass flowering). Observations concerned following variables: flowering, its intensity, its frequency, and cherry filling rate.

For flowering, the aim was to record the presence or absence of flowers on the trees and to count them on each sampled node (to determine the female fertility category F) throughout the year (each month).

Flowering frequency determined by counting number of flowering events per month throughout each year.

Flowering intensity assessed on an ordinal scale from 0 to 4, based on a visual assessment of the proportion of open flowers among all floral structures (closed buds and open flowers) present on the tree. The assessment grid constructed in an operational manner using flowering logic progression described by the BBCH classification applied to coffee plants, without resorting to individual flower counting (Arcila-Pulgarín *et al.*, 2002) [2]. This correspondence remains a qualitative approximation intended to link visual assessment to the

phenological sequence coded by BBCH, without claiming strict metric equivalence.

Cherry filling rate involved counting young fruits number after fertilization and before fruit ripening (before maturity) to classify them by female fertility. Fruits categorized based on the

cherry filling rate, natural (free) fertilization was observed over the months. For this purpose, 100 cherries were randomly collected using cross-section at different canopy levels (top, middle, bottom) during months' observation.

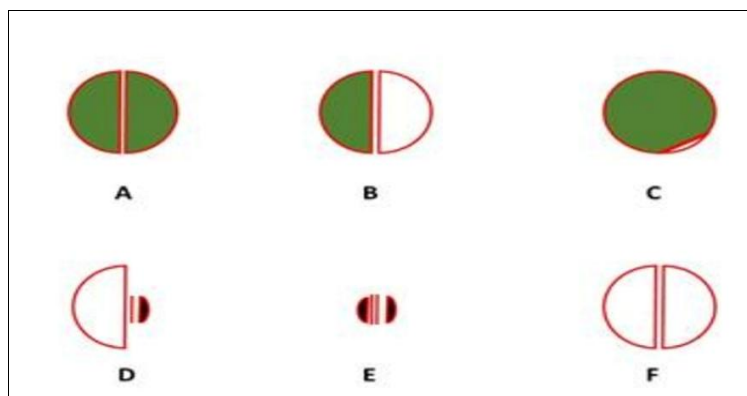


Fig 2: Illustrates the morphological type of cherries as defined by Reffye (1974) ^[27].

Figure 2. Morphological types of coffee cherries (Reffye, 1974) ^[27]. Categories: A, cherry with two normal seeds; B, cherry with one empty locule and one normal seed (late endosperm abortion); C, cherry with one curved (caracol) seed and one empty scale (early ovule abortion); D, cherry with one empty locule and one scale; E, cherry with two empty locules (late abortion); F, ovary not fused or drying out within two months after fertilization.

Statistical analysis

The variables studied include flowering (the presence or absence of flowers on the trees), the frequency and intensity of flowering, and the filling rate of the cavities. These variables were related to the observed climatic parameters over three reproductive cycles of coffee plants in Yangambi. Collected data fed into structured spreadsheets (Excel files, each corresponding to a variable under study) and then subjected to descriptive analyses (means).

Statistical analyses focused on:

- **Time Series:** To visualize the cycles of presence, frequency, and intensity of flowering;
- **Pearson correlation:** To test the link between flowering, flowering frequency, flowering intensity, and cherry filling

rate with climatic variables (precipitation, temperatures, and humidity);

- **Beta Regression:** To test the seed filling rate (values between 0 and 100%);
- **Kruskal-Wallis test with Dunn's post-hoc test:** To compare the different variables across various months of the year and over three years of observation;
- **Principal Component Analysis (PCA):** To visually synthesize the climatic parameters influencing flowering and cavity filling rates;

Time-Log Analysis and Beta Regression: used to analyze the delayed effect of climatic factors (to determine whether climatic conditions in a previous month influence flowering and cherry filling in a subsequent month). For this, we used R with the RStudio interface (version 4.5).

Results

Climatic parameters

Results related to climatic parameters are presented in Figures 3 and 4 below:

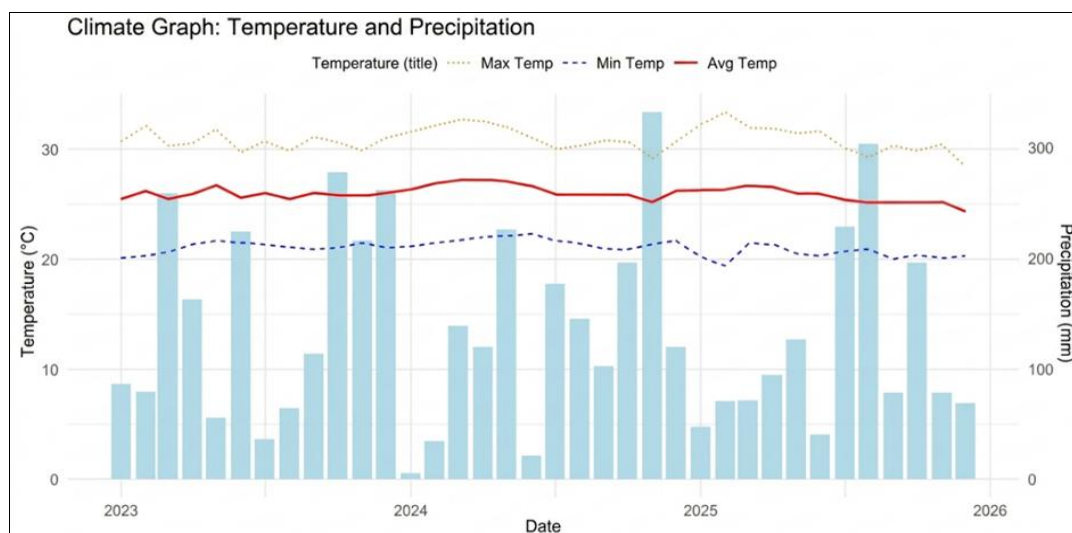


Fig 3: Temperature and rainfall from 2023 to 2025 at INERA Yangambi climatic station

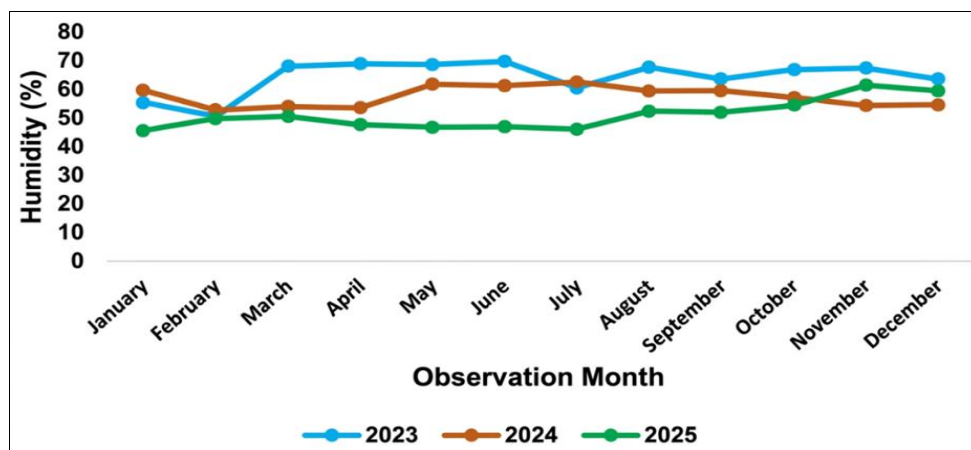


Fig4: Percentage of air relative humidity

The climatic data observed at Yangambi between 2023 and 2025 indicate generally warm conditions, with high temperatures throughout the entire study period. Among the three years studied, 2024 shows the highest values, reflecting intensified local warming. Relative humidity shows a general downward trend over these three years. Although this decrease remains moderate, there is a shift towards drier atmospheric conditions.

The average temperatures confirm these observations. In 2023, the monthly averages ranged between 25.4 and 26.7 °C, with an annual average of 26 °C. In 2024, they are higher, often reaching 26.4-27.25 °C during the hottest months, with an annual average fluctuating between 26.35 and 26.99 °C. In 2025, the values return close to those of 2023, although a decrease in December (24.35 °C) causes a slight reduction in the annual average, which ranges from 25.68 to 26.4 °C.

Precipitation varied from one year to another. In 2023, it is relatively well distributed, with several months experiencing heavy rainfall, notably in March, October, November, and December. In 2024, rainfall is very low at the beginning of the

year, then becomes significant during the rainy season. In 2025, rainfall is more irregular, with notable peaks and fewer rainy periods, indicating high intra-annual variability.

Overall, annual totals remain high (around 1800 to 2200 mm), but the distribution of rainfall becomes more irregular. In 2023, rainfall is more consistent; in 2024, the dry season is more pronounced at the start of the year; in 2025, the alternation between wet and dry months is more distinct. Relative humidity generally remained between 50% and 69%, but gradually decreased from 2023 to 2025, with lower values in 2025. These climatic conditions can influence the development of the coffee plant, particularly the flowering phases, which are strongly dependent on temperature and water availability.

Annual variations in flowering

Figure 5 presents the results relating to the variation in the number of flowering trees over three consecutive years (2023-2025).

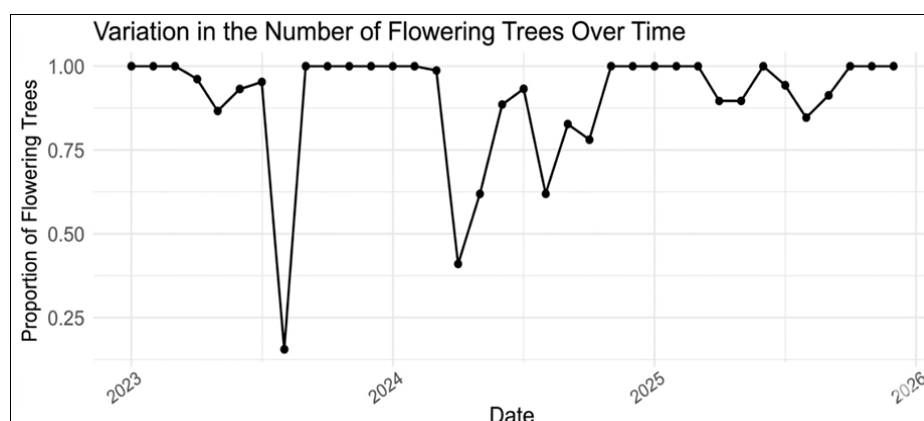


Fig 5: Variation in the number of flowering trees over time

The flowering (fig. 5) occurs almost continuously throughout the year, regardless of the period or year analyzed, with a majority of trees in bloom, often up to 100%. In 2023, all the trees flowered from January to March (100%).

This rate decreased slightly in April (96.2%) and May (86.7%), then rises again between June and July (from 93.3% to 95.2%). A marked drop appears in August (15.2%), followed by a return to 100% from September to December. The same dynamic observed at the beginning of 2024, with 100% in January and February, then 99.0% in March. A significant decline observed in April (41.0%), followed by a gradual increase in May

(61.9%), June (88.6%), and July (93.3%).

The rate decreases again in August (61.9%), remains between 78.1% and 82.9% in September and October, then reaches 100% in November and December. Finally, in 2025, the flowering remained abundant throughout the year, fluctuating between 89.5% and 100%. Over the entire 36 months of observation, 26 months (72.2%) showed a flowering rate of 100%.

Two months stand out with significantly lower values: August 2023 (15.2%) and April 2024 (41.0%). Results showed that coffee trees flowered through the year; the climatic conditions, characterized by a succession of humid periods and temperature

variations, explain this continuous flowering, which disrupts the usual rhythm of the coffee tree's reproductive cycle.

Statistical analysis of climatic variables (precipitation and temperature at different time logs) showed low explanatory power ($R^2 = 0.176$) and an overall non-significant test ($p = 0.215$). These variables explain 17.6% of the variability in flowering. The regression models tested, combining different forms of precipitation and temperature variables shifted in time, showed low F-statistics and high p-values (ranging from about 0.24 to 0.94).

The flowering of Robusta coffee at Yangambi does not depend

solely on the analyzed climatic variables. Other factors influenced the triggering and maintenance of flowering, interacting with the intra-annual variability of precipitation and temperatures. These results indicated a disruption of the physiological functioning of the coffee tree, caused by a succession of precipitation events and temperature fluctuations over the months.

Annual variations in flowering frequency

The results related to flowering frequency are presented in Figure 6.

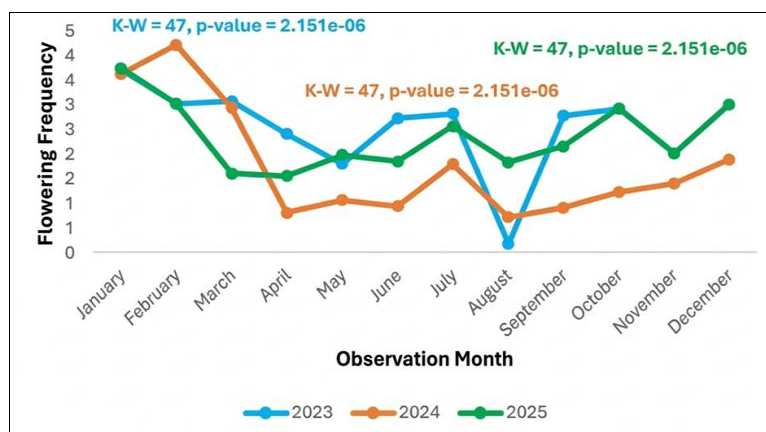


Fig 6: Frequency of flowering

The flowering frequency (number of episodes per month) varied between 0 and 4 throughout the studied period. The year 2024 exhibits the lowest frequencies, with a dominance of months with only one episode, in contrast to 2023 and 2025, where 2 to 4 episodes were more common. These observations highlighted a multimodal phenological dynamic, with a main peak at the beginning of the year (January-February) and a second, more spread out, between September and December. The Kruskal-Wallis test confirms a significant temporal variation ($W = 47$;

$p < 0.001$). The regression model based on precipitation with a two-month lag (Precipitation_lag2) yields a coefficient $\beta = 0.0032$ ($p = 0.087$; $R^2 = 0.089$). An increase of 100 mm in precipitation corresponds to an average rise of approximately 0.32 flowering episodes per month.

Annual variations in the intensity of flowering

Figure 7 illustrates the results of the flowering intensity over the years.

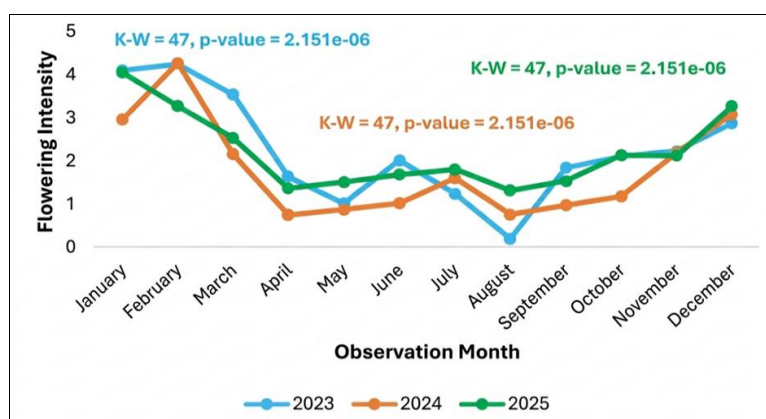


Fig 7: Intensity of coffee flowering according to annual observation at INERA Yangambi

Figure 7 shows the flowering intensity on a scale from 0 (no flowers) to 4 (intense flowering). The highest values are concentrated in the first quarter, peaking in February 2024. Monthly fluctuations in intensity are significant (Kruskal-Wallis, $W = 47$; $p < 0.001$). A general decline observed between April and June, with a marked minimum in August, notably in 2023, when the intensity falls to almost zero. From September onwards, a gradual recovery took place, with more stable levels from one year to the next.

The regression model based on precipitation with a two-month lag (Precipitation_lag2) shows a significant positive effect ($\beta = 0.0034$; $p = 0.046$; $R^2 = 0.118$). An increase of 100 mm in precipitation corresponds to an average rise of about 0.34 units in flowering intensity.

Monthly and annual variations in the ovary cherry filling rates.

Figure 8 below presents the occupancy rates of the compartments based on monthly and annual flowering periods.

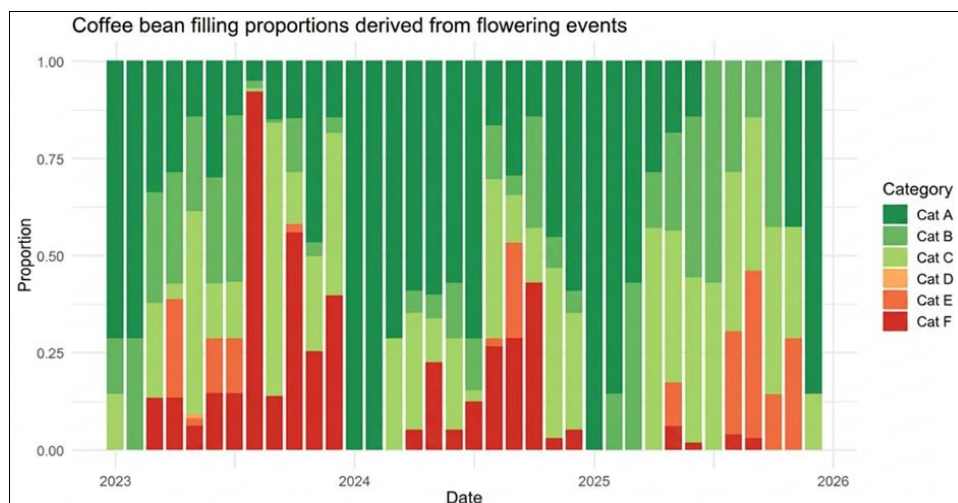


Fig 8: Coffee Bean Filling Proportions Derived from Flowering Events

Figure 8. Figure 2. Morphological types of coffee cherries (Reffye, 1974) ^[27]. Categories: A, cherry with two normal seeds; B, cherry with one empty locule and one normal seed (late endosperm abortion); C, cherry with one curved (caracol) seed and one empty scale (early ovule abortion); D, cherry with one empty locule and one scale; E, cherry with two empty locules (late abortion); F, ovary not fused or drying out within two months after fertilization.

A dominance of fruits with two normal seeds (category A) was observed throughout much of the study period, with monthly proportions ranging from 0% to 100%. These filling rates were often higher at the beginning and end of each year (ranging from 71% to 100%).

Furthermore, the other categories (B to F), associated with varying levels of abortion or malformation, showed significant variability over the months. This indicates that the flowering periods in January and February consistently exhibit the best performance, with high proportions of normal fruits. Conversely, the months from July to October correspond to

critical phases, characterized by a sharp decline in well-formed fruits and an increase in anomalies.

Statistical models indicated a positive effect of temperature on the proportion of category A ($\beta = 0.230$; $p = 0.012$), as well as a marginal effect of precipitation. For category C, the maximum temperature has a significant negative effect ($\beta = -0.084$; $p = 0.020$). Similarly, for category E, the maximum temperature exerts a significant negative effect ($\beta = -0.057$; $p = 0.003$; $R^2 = 0.246$), with no notable effect from precipitation. These results show that moderate thermal conditions, combined with sufficient water availability, promote normal seed development, whereas more restrictive conditions are associated with increased anomalies. The observed variability, however, remains linked to multiple factors beyond climatic conditions.

Climate determinism on floral variables

Figure 9 illustrates the climatic determinism on the floral variables of the coffee plant.

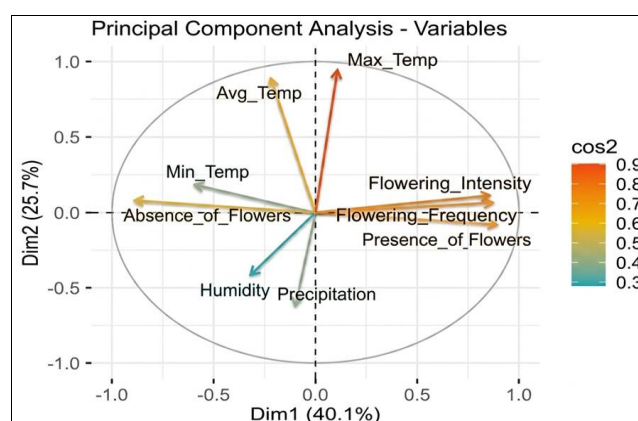


Fig 9: Climatic determinism on floral variables

There is a marked negative linear relationship between periods of heavy rainfall and high humidity and the onset of coffee flowering. This indicates that the initiation of flowering and the differentiation of buds in the coffee plant require a prior phase of water stress (dry season). However, an excess of water during flowering causes mechanical abscission of the flowers, impairs pollen viability, and prevents the expression of a widespread and intense flowering, which explains the diametrically opposite positioning of these vectors on the graph (fig. 9).

Regarding temperature, an increase in minimum temperatures has led to a decrease in the frequency and floral load of coffee plants. Meanwhile, variations in daily maximum temperatures have exerted no direct linear influence (positive or negative) on the success gradient or the intensity of flowering. Although the plant's metabolism depends on heat, the opening of the fully developed coffee flower is modulated by the plant's internal water potential and internal hormonal stimuli rather than by daily temperature peaks.

The climatic determinism on the cherries filling rate

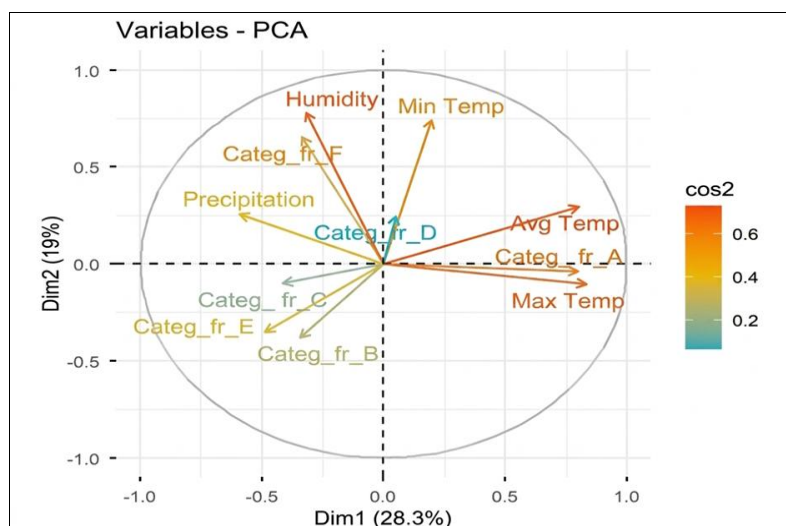


Fig 10: Climatic determinism on the cherries filling rate

The studied categories are not randomly distributed with respect to climatic parameters. Dimension 1 can be interpreted as a heat index, while Dimension 2 relates to a water supply index. Categories A and E constitute the two most discriminating climatic signatures of the model, whereas category D appears to be 'temporally or spatially independent' of the direct meteorological fluctuations captured by the sensors.

Discussion

The climatic conditions observed in Yangambi between 2023 and 2025 are part of a warming trend already documented in the region. High temperatures, peak in 2024, confirm the gradual increase in the average annual temperature and the increased frequency of hot days and nights (Kasongo *et al.*, 2023; 2024) [20]. The progressive decrease in relative humidity aligns with long-term trends associated with rising temperatures (Kasongo, 2020) [19, 21]. Precipitation remains abundant, but its distribution becomes more contrasting, with a strengthening of seasonality characterized by intense rainy episodes and more pronounced dry periods (Kasongo *et al.*, 2023; Rainiaux *et al.*, 2018) [26].

Under these conditions, coffee flowering appears continuous throughout the year, with 72.2% of months showing 100% of trees in bloom. This pattern differs from traditional coffee systems, in which flowering is seasonal and synchronized following a period of water deficit (Trottet, 2021).

The absence of a marked floral rest period at Yangambi is linked to nearly constant rainfall, which limits the development of sufficient water stress to structure the reproductive cycle. This mechanism aligns with the work of Alvim (1960) [1] and Crisosto *et al.* (1985), who show that flowering depends on an alternation between water deficit and rehydration rather than cumulative rainfall.

The frequency of flowering highlights a multimodal dynamic, with a main peak at the beginning of the year and a more diffuse second peak at the end of the year. This organization is consistent with observations by DaMatta *et al.* (2007) [16], who relate flowering to variations in the plant's water status. The irregularity observed, especially in the latter part of the year, resembles the multiple flowering events described by Camargo (2010) [7] in unstable climatic contexts. The low explanatory power of the rainfall-based model ($R^2 = 0.089$) confirms that the frequency of flowering episodes depends more on the succession of dry and wet phases than on monthly rainfall amounts.

The intensity of flowering follows a similar pattern, with high values at the start of the year and lower values mid-year. The role of water in preparing floral buds is well established (Parada-Molina *et al.*, 2025) [24], while the combination of water deficit and rehydration remains crucial for abundant flowering (Alvim, 1960; Schuch *et al.*, 1992) [1, 28]. The variations observed in the end of

the year may be linked to competition for assimilation, with a heavy fruit load limiting the expression of secondary flowering (Vaast *et al.*, 2005) [30].

The filling of the coffee cherries shows high variability, with good performance at the beginning of the year and marked deterioration between July and October. This period corresponds to an increase in anomalies (caracoli grains, empty cherries, abortions), already associated with environmental stresses and physiological imbalances (Barbosa *et al.*, 2015; Carvalho & Monaco, 1969; Pezzopane *et al.*, 2007) [3, 9, 25]. The limitation of carbon resources during periods of high reproductive load also contributes to these abortions (Vaast *et al.*, 2005) [30].

Principal component analysis highlights a clear opposition between hydric variables (rainfall, humidity) and flowering parameters. Continuous humidity is associated with reduced floral expression, consistent with Borchert *et al.* (2004) [5]. The rise in minimum temperatures, particularly at night, is associated with decreased floral activity due to increased respiration at the expense of carbon reserves (Craufurd & Wheeler, 2009) [11].

Conversely, maximum temperatures do not directly affect the observed ranges unless critical thresholds are reached (Cleland *et al.*, 2007) [10]. These results confirm that coffee flowering depends on a balance between hydric and thermal conditions, and that its desynchronization at Yangambi occurs within an increasingly variable climate context, in line with classical phenological models (Camargo, 2010; Carr, 2001) [7, 8].

The correlation between humidity and failure of fruit set (Category F) can be interpreted through Cannell's (1985) "Source-Sink" theory, which states that very high relative humidity (saturation) reduces vapor pressure deficit (VPD), thereby blocking leaf transpiration and the overall transpiratory flux of the coffee plant. Without this mechanism, the transport of sap and nutrients to young fruits (which act as primary metabolic "sinks") is disrupted, causing their early physiological abortion.

Conclusion

This study highlights the high sensitivity of the Robusta coffee tree to microclimatic fluctuations in Yangambi. The recorded results indicate that the water regime is the primary structuring factor for flowering, while rising minimum temperatures and high humidity limit its expression. Climatic disturbances are accompanied by increased anomalies in fruit development.

In this context, the adaptation of production systems relies on strategies to mitigate climatic constraints, notably through agroforestry and the selection of genotypes tolerant to thermo-hydric stresses.

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Conflicts of interest

The authors declare no conflict of interest.

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