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Phenology of *Coffea canephora* from different maturation cycles

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Abstract

The vegetative and reproductive development of *Coffea canephora* is affected by climatic variations; however, how environmental signals affect its phenology, especially across different maturation genotypes, remains poorly understood. In this study, we investigated the effects of climatic conditions on the vegetative growth, flowering, and fruiting of *C. canephora* genotypes during different maturation cycles. During the 2021–2022 harvest, early genotypes 104 and A1, intermediate genotype P2, and late genotype 143 were studied in Marilândia, ES, Brazil. A phenological scale of the reproductive period was developed, along with evaluations of vegetative development, productivity, and fruit maturation stages. The main flowering occurred in September. Distinct flowering patterns were found, with a large, medium bloom occurring in July in the early clones. Flowering occurred from July to October 2021 and in February and May 2022. The late genotype 143 presented the highest yield, with 92.6% of the fruits reaching the cherry stage. Compared to the other genotypes, the A1 genotype required 21% more ripe fruit to make up a bag of coffee, indicating a loss of yield in the immature stages (45%). A1 and P2 showed the highest growth. The vegetative growth rates peaked in spring and summer, which coincided with periods of the highest precipitation (86% of the annual precipitation). Factors such as long days, average minimum temperature, and humidity were associated with an increase in growth rates, whereas maximum temperature and solar radiation in summer negatively affected vegetative growth.

Plain Language Summary

Climatic variations impact growth and reproduction of *Coffea canephora*, but their effects on different maturation genotypes remain largely unknown. This study investigated how climatic conditions impact the growth, flowering, and fruiting of early, intermediate, and late genotypes. The main flowering occurred in September. Distinct flowering patterns were found, with a large, medium bloom occurring in July in the early clones. Compared to the other genotypes, the A1 genotype required 21%

more ripe fruit to make up a bag of coffee, indicating a loss of yield in the immature stages (45%). A1 and P2 showed the highest growth. The vegetative growth rates peaked in spring and summer, which coincided with periods of the highest precipitation (86% of the annual precipitation). Factors such as long days, average minimum temperature, and humidity were associated with an increase in growth rates, whereas maximum temperature and solar radiation in summer negatively affected vegetative growth.

1 | INTRODUCTION

Coffee production is extremely important economically around the world, especially the production of two species, *Coffea arabica* (arabica) and *Coffea canephora* (robusta and conilon groups); Brazil is the main producer of these species (FAO, 2022). Although *C. arabica* is traditionally the most-produced coffee in Brazil, the cultivation of *C. canephora* has increased due to its productivity, resistance, and adaptability (Kath et al., 2020).

Flowering and fruit ripening times are critical stages in the life cycle of *C. canephora* (Kath et al., 2023). The irregular induction of flowering leads to uneven fruit maturation, affecting grain quality (Miranda et al., 2020). Additionally, some studies have found changes in the phenology of *C. canephora* flowering, such as delays or advances depending on precipitation and temperature (Kath et al., 2023). Some studies have shown that induction can begin in February and reach the peak of floral transcription in June during cooler temperatures (Cardon et al., 2022).

Temperature and precipitation strongly influence the production of *C. canephora* (Kath et al., 2023; Venancio et al., 2020). Phenomena such as El Niño and La Niña have become more common in Brazilian coffee regions and threaten productivity (Richardson et al., 2023; K. A. Silva, de Souza Rolim, et al., 2020). The water deficit associated with high temperatures and irradiance is the environmental factor that affects the production of *C. canephora* the most, as highlighted by Venancio et al. (2020), with a reduction in productivity of up to 50% at average annual temperatures above 25.1°C.

Studies on the phenology of *C. canephora* under field conditions are scarce and do not consider the effects of genotypes with different maturation cycles. Salazar et al. (2019) found that climatic variations significantly affect the phenological patterns of *C. canephora*. Warm nights are considered to be the main cause of early flowering in *C. canephora* (Kath et al., 2023). Temperatures below 17°C and above 31.5°C decrease the growth rate of *C. canephora* branches, whereas temperatures between 21°C and 27.5°C are considered ideal (Partelli et al., 2010, 2013).

The relationships among climate, phenological development, and environmental factors are important for supporting effective agricultural technologies, which aim to manage vegetative growth, synchronize flowering, and optimize fruit production (Salazar et al., 2019). Although Kath et al. (2023) did not specify variations between genotypes, early flowering increased the sensitivity of *C. canephora* production to thermal stress and precipitation.

The main hypothesis of this study was that climatic variations, including temperature, precipitation, and photoperiod, exert unique effects on the vegetative development and production of *C. canephora* genotypes in different maturation cycles. We also tested the hypothesis that genotypes with an early maturation cycle are more sensitive to climatic variations, presenting greater fluctuations in the rate of vegetative growth and productivity in response to environmental changes than are genotypes with intermediate and late maturation cycles. Thus, we investigated the effects of climatic conditions on the vegetative growth, flowering, and fruiting of *C. canephora* genotypes during different maturation cycles.

2 | MATERIALS AND METHODS

The experiment was conducted at the Experimental Farm of the Capixaba Institute for Research, Technical Assistance and Rural Extension (INCAPER), which is located in the municipality of Marilândia (19°24′19″ S, 40°32′20″ W; 188 m altitude), and the soil was classified as a dystrophic Oxisol. Genotypes of *C. canephora* from the conilon group belonging to the INCAPER Germplasm Bank were evaluated and characterized as having early, intermediate, and late maturation cycles. The precocious genotypes were clones 104 registered as 401 of Marilândia and A1 of the Andina cultivar (Partelli et al., 2019), which corresponded to 108 of Diamante Incaper 8112. The intermediary genotype was P2, which is 411 of the Diamante Incaper 8112. The late genotype was 143, registered as 306 of Centenária ES8132.

The crop was 3 years old, and the genotypes were grown in full sun with a spacing of 3 m × 1.5 m in the rain-fed system.

In this study, we referred to the genotypes as 104, A1, P2, and 143, as this is how they are known in the field.

Information on the climatic conditions was obtained from an automatic meteorological station belonging to the National Institute of Meteorology (INMET) located in the experimental area. The photoperiod was obtained from the SOLAR TOPO (2022) electronic platform. Potential evapotranspiration (Etp) was determined using the method described by Hargreaves and Samani (1985). The meteorological variables analyzed covered the period from July 2021 to July 2022 and included average, minimum, and maximum temperatures (˚C), average relative humidity (%), solar radiation (kJ m^{-2}), accumulated precipitation (mm), Etp, and photoperiod.

The air temperature increased in summer and decreased in July (Table 1), marking the Brazilian winter period. The average annual air temperature was 24.53˚C (June 2021 to July 2022), with the lowest monthly minimum value of 15.28˚C recorded on June 22 and the maximum value of 33.53˚C recorded on January 22. The peak average humidity was recorded in December, reaching 77.1%. The annual precipitation reached 960.60 mm, with rain occurring between October and February, representing 87% of the total annual precipitation. The highest Etp was 182.80, and the solar radiation was 1553.81 kJ m^{-2} in January, which corresponded to the longest period of light.

Phenological development was assessed biweekly, considering 12 plants of each genotype, with the selection of one branch per plant for analysis in the median portion of the crown to monitor the development of fruits and floral buds of the third and fifth nodes. These observations were recorded photographically, and the developmental stages were classified according to the scale developed by Pezzopane et al. (2003) and Dalvi et al. (2017). In total, 10 stages of bud development were identified: (1) dormant bud, (2) swollen bud, (3) budded, (4) flowered, (5) post-flowered, (6) pin head, (7) expansion (expansion until changing from sepia green to green), (8) green, (9) cane green, and (10) cherry. The phenological stage considered for each genotype was the one with the highest repeatability (mode) in each evaluation.

2.1 | Vegetative growth assessments

After the harvest in 2021, one orthotropic branch and two primary plagiotropic branches were selected from each plant, which emerged from the orthotropic branches in the upper third of the plant canopy (Figure S1). Vegetative growth was assessed biweekly. The vegetative characteristics evaluated were the length of orthotropic and plagiotropic branches using a graduated ruler and the number of plagiotropic branches of orthotropic branches via direct counting. From these data, the monthly growth of orthotropic branches (cm), length of plagiotropic branches (cm), and number of plagiotropic branches were obtained. The growth rate of the plagiotropic branches between the previous assessment and the next assessment was also calculated, and for each season, the orthotropic branch growth rate (OGR; cm), plagiotropic branch growth rate (PGR; cm), and plagiotropic branch number rate (PNR) were calculated. The OGR, PGR, and PNR were obtained from the difference between the initial and final values of each station.

Core Ideas

- The results revealed different patterns of resistance among the early, intermediate, and late genotypes.
- Early flowering was associated with early genotypes.
- Genotypes A1 and P2 were prominent in terms of growth.
- Early clones were susceptible to humidity, high minimum temperatures, and long photoperiods.
- A chronological relationship was found between flowering and the formation of branch nodes.

2.2 | Production and yield data

The plants were harvested according to the maturation cycle between June and July 2022 (June 09, June 29, and July 27). After harvesting, the genotypes were categorized based on their maturation stage, according to the scales described by Pezzopane et al. (2003) and Dalvi et al. (2017). The total production per plant was evaluated using an electronic scale (capacity of 150 kg). The percentage of floating fruits (float; %) and the uniformity of maturation were determined by visually examining the phenological stages of maturation. A sample from each plant was selected to count the phenological stages, and the values were expressed as a percentage using the following calculation:

$$\text{Maturation stage} = \frac{\text{Total no. of fruits in the sample} \times 100}{\text{No. of stage fruits in the sample}}$$

The floating fruits and impurities were removed, and samples of each plant were separated, weighed, and dried to a constant weight in an oven with forced air circulation at 38˚C until they reached a humidity value of about 12. The weights were determined using a Gehaka grain moisture meter (G600); all fruits were peeled before assessment. The humidity was adjusted to 12% using the following equation:

TABLE 1 Average data on the meteorological parameters of maximum temperature (Max. T., °C), minimum temperature (Min. T., °C), average temperature (Avg. T., °C), average relative humidity (Hum., %), accumulated precipitation (Precipitation, mm), solar radiation (Radiation, kJ m^{-2}), potential evapotranspiration (Etp), and photoperiod (Phot.). Monthly averages from June 2021 to July 2022.

Months	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Annual
Max. T.	28.06	28.97	31.4	29.54	29.2	30.04	33.53	32.48	33.5	33.3	29.69	28.63	28.27	30.71[a]
Min. T.	16.76	17.85	20.5	21.44	19.95	21.11	21.96	22.27	21.26	19.97	17.60	15.28	16.25	19.62[a]
Avg. T.	24.37	25.66	27.13	25.46	23.79	24.67	26.65	25.93	26.10	25.27	22.31	20.5	20.87	24.53[a]
Hum.	66.65	68.00	65.10	73.48	77.12	77.10	70.73	75.57	72.11	69.68	71.16	71.42	73.31	72.07[a]
Precipitation	1.00	2.20	2.20	97.60	162.80	197.60	97.60	284.20	31.80	12.00	44.60	3.40	24.60	960.60[b]
Radiation	1306.16	1266.07	1306.39	1130.56	1178.23	1138.92	1553.81	1352.86	1550.15	1350.12	1058.89	1085.43	1003.25	1247.89[a]
Etp	103.42	125.63	143.04	135.64	143.92	153.43	182.8	146.95	163.98	139.89	108.57	95.27	98.54	1637.66[b]
Phot.	10.88	11.26	11.74	12.30	12.79	13.14	12.98	12.41	12.00	11.36	11.09	10.56	10.88	142.51[b]

[a]Monthly average.
[b]Sum of monthly average.

$$\text{Corrected humidity} = \frac{\text{Weight of ground coffee} \times \left(1 - \frac{\text{Moisture obtained by looting}}{100}\right)}{0.88}$$

The yield index was estimated by the weight reduction that occurred while drying, based on the relationship between the weight of the dried coffee cherry and the weight of the coffee from the crop. With these key points, the yield in kilograms of ripe coffee per bag of 60 kg of crushed fruit grains was calculated using the following equation:

$$\text{kg of ripe coffee/kg of crushed coffee} = \frac{\text{Wet sample weight}}{\text{Corrected humidity}} \times \text{Sugarcane}$$

2.3 | Statistical analysis

A randomized block design was adopted, with three replications of four plants in a plot scheme divided over time. The plots represent genotypes from different maturation cycles (early, intermediate, and late), whereas the subplots represent the evaluation times. The growth variables were analyzed by comparing the genotypes in the last evaluation period. A linear regression analysis was conducted to model the relationships between the meteorological variables and the growth of the plagiotropic branches in the fortnightly assessments. All results were considered to be statistically significant at $p < 0.05$.

Statistical analyses were also conducted considering growth rates in four seasons (winter, August–September; spring, September–December; summer, December–March; and autumn, March–June) and four genotypes. The mean values were compared using the Scott–Knott cluster test, with a significance level of 5%. The growth rate and climate data from the four seasons were used to conduct principal component analysis (PCA) and Pearson correlation analysis (r). All analyses were conducted using the R software (*R Studio 4.2.1*).

3 | RESULTS

3.1 | Phenological stages

The photographs that constitute the assessment scale for the phenological stages of *C. canephora* are shown in Figure 1. The morphological differentiation stages of the flowers in the plagiotropic branches responsible for the production in the following year were recorded. By the end of the observations, we could identify Stages 1 and 2 in the evaluated branches (Figures 1 and 2).

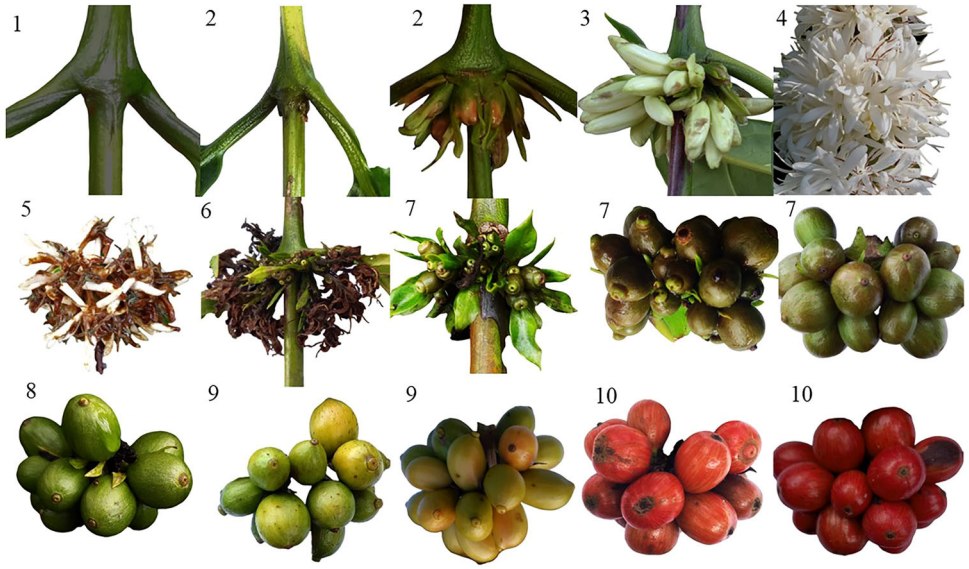

FIGURE 1 Phonological scale of the phenological stages for *Coffea canephora* using the phenological scale defined by Pezzopane et al. (2003) and Dalvi et al. (2017). The identified stages were as follows: (1) dormant bud, (2) swollen bud, (3) buttoned, (4) flowering, (5) post-flowering, (6) pin head, (7) expansion (expansion until changing from sepia green to green), (8) green, (9) cane green, and (10) cherry.

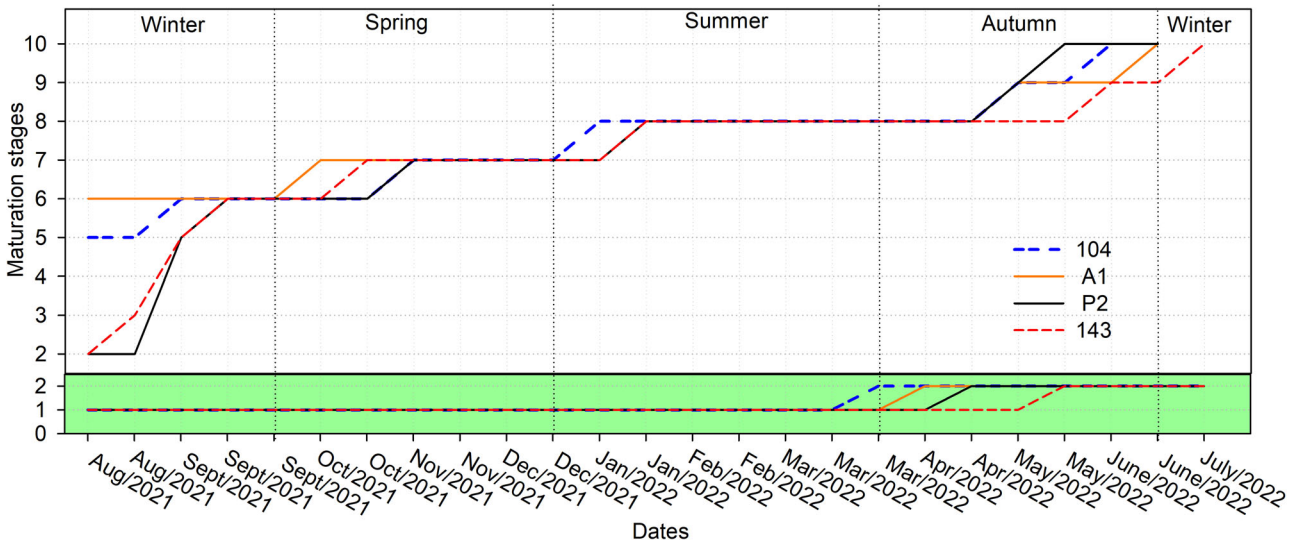

FIGURE 2 Assessment of phenological stages. Development of floral buds in green and fruits in white. The identified stages were as follows: (1) dormant bud, (2) swollen bud, (3) buttoned, (4) flowering, (5) post-flowering, (6) pin head, (7) expansion (expansion until changing from sepia green to green), (8) green, (9) cane green, and (10) cherry.

Between July and August, emissions from one or two pairs of small leaves were observed (Figure 3F). In these buds, flowering occurred in February (Figure 3C). Two main blooms were identified for genotype 104, four for A1, one for P2, and three for 143, characterized by the total bloom and the average bloom (Table 2; Figure 3A,B).

The main flowering event was recorded in September (Table 2), occurring 9 days after the first rains (Tables S1 and S2). However, for the early genotypes, the reproductive phase began in July (Table 2). In August, most of these genotypes had fruits predominantly at Stage 6 (pin head) (Figures 1 and 2). Genotype A1 presented variations in its flowering pattern, with atypical occurrences (Table 2).

After fertilization, pellet formation and fruit expansion occurred (Figures 1 and 2). This stage occurred from September to January. From January to April, all genotypes were in the green phase, with the longest duration. The subsequent green cane stage is the shortest, lasting up to 4 weeks. The transition from the green cane stage to the cherry stage began

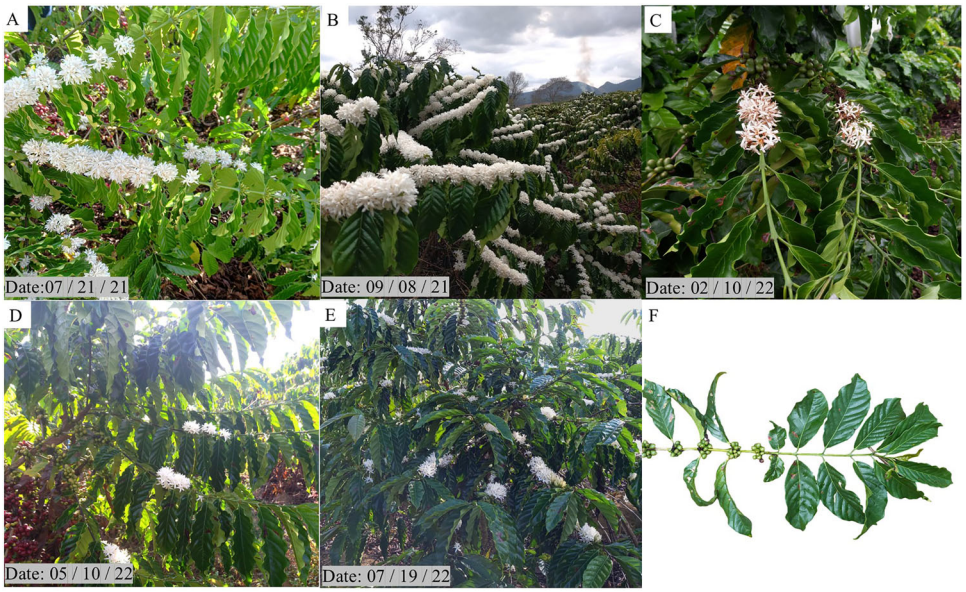

FIGURE 3 Description of flowering types with their dates and leaf patterns. (A and E) MF, medium flowering; (B) F, full bloom; (C and D) SF, saute flowering; (F) representation of a branch with a leaf pattern of small leaves.

TABLE 2 Characterization of flowering and harvesting times of early, intermediate, and late genotypes.

Months	Dates	104	A1	P2	143
July	July 21, 2021	MF	MF	NF a SF	NF
August	August 18, 2021	NF a SF	SF	SF	MF
August	August 26, 2021	SF	B1-MF, B3-F, B2-NF	SF	MF
September	September 08, 2021	F	F	F	F
October	October 18, 2021	SF	SF	SF	SF
February	February 2022	SF	SF	SF	SF
May	May 10, 2022	SF	NF	NF	NF
July	July 19, 2022	NF e SF	SF e MF	NF	NF
Harvest dates		June 09, 2022	B1-June 09, 2022; B2 and B3-June 29, 2022	June 29, 2022	July 27, 2022

Note: B1–B3 refer to the block. F, full flowering; MF, medium flowering; SF, saute flowering; NF, did not flower.

in May and ended in July, when a significant reduction in Etp was recorded.

Maturation was observed in May for genotype P2 (Figure 2), which corresponded to 37 weeks. Genotypes 104 and A1 completed fruit maturation in June, which was equivalent to 39 and 41 weeks, respectively. The maturation of genotype 143 occurred in July, which corresponded to 43 weeks. However, the methods used to determine the duration of phenological stages have limitations, as they consider only the branch of a portion. As the flowering times are different, the fruits on the plants might be at different stages of maturity, which can directly affect the time of harvest.

3.2 | Production

When the yield of a 60 kg bag of processed coffee was calculated, the values were greater for the A1 genotype (307.2 kg), which presented a greater percentage of green beans (33.7%), and 55.5% of the ripe fruits had reached maturity (Figure 4A,D). Genotype 104 (236.3 kg) presented percentages of green and cane green grains of 8.2% and 8.6%, respectively, along with 67.5% cherry fruits, 5.5% dried fruits, and 10.1% raisins (Figure 4A,D). Genotype P2 (253.2 kg) consisted of 19.7% green grains, 11.9% green cane, and 67.1% cherry, raisin, and dried fruits (1.3%); genotype 143 (270.6 kg) did not differ significantly (Figure 4A,D).

Genotype 143 presented the highest yield in kilograms of ripe coffee per kilogram of crushed coffee, besides presenting the highest percentage of fruits at the cherry ripening stage (>90%) (Figure 4B). This genotype also presented the lowest percentages of green fruits (5.8%) and cane green fruits (1.6%) (Figure 4D). No significant differences were detected between the other genotypes evaluated (Figure 4B). Regarding the float variable, no significant differences were found between the genotypes (Figure 4C).

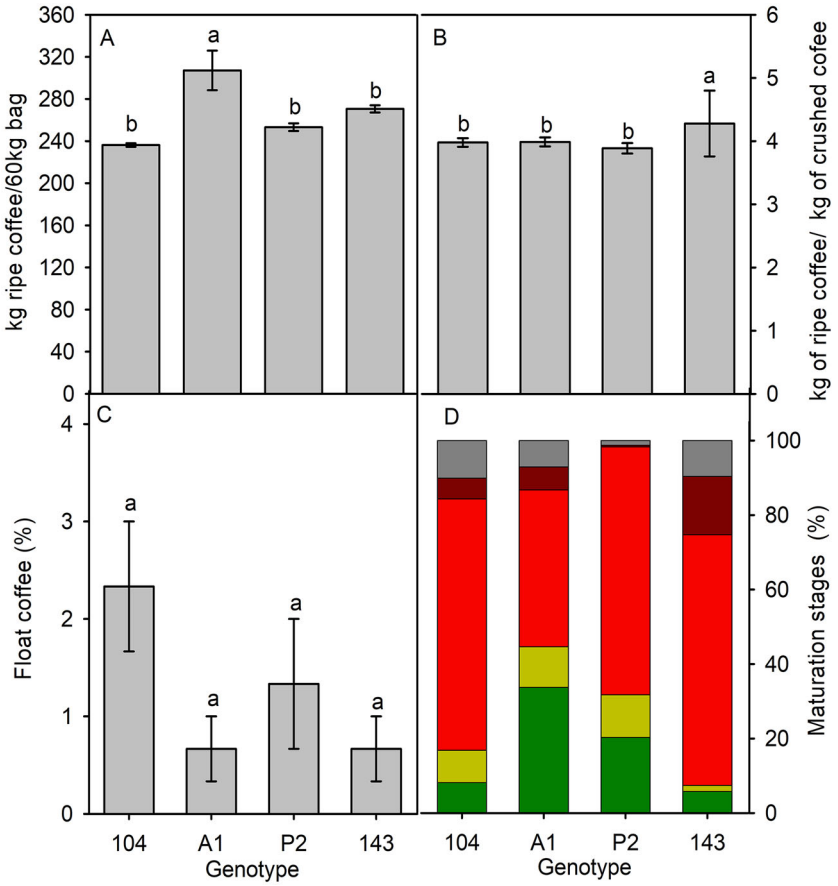

FIGURE 4 (A) kg of ripe coffee/60 kg bag, (B) kg of ripe coffee kg^{-1} of crushed coffee, (C) floating coffee (%), and (D) maturation stages: green (■), cane green (■), cherry (■), raisin (■), and dry (■) stages of early-maturing genotypes 104 and A1, intermediate P2, and late 143 at harvest. Means followed by the same letter in the same column do not differ significantly from each other, according to the Scott–Knott cluster test ($p \leq 0.05$). The bars indicate the standard deviation from the mean.

3.3 | Growth variables

The highest values of orthotropic branch length and plagiotropic branch length were observed for genotypes A1 and P2 (Figure 5A,C). From October to November, branch growth increased, with clone P2 exhibiting a prolonged growth phase compared to the other genotypes.

Each graph in Figure 6 shows the dispersion of growth data in the context of meteorological variables. A positive trend in the line was observed for all genotypes. The R^2 value was not satisfactory for genotype 143 for any variable. For minimum temperature, the calculated minimum zero growth points varied between genotypes, with values of about 14.5˚C for genotype 104, 14.8˚C for genotype A1, 14.6˚C for genotype P2, and 14.5˚C for genotype 143. The growth rates were generally the highest when the minimum temperature was about 20˚C or higher.

The minimum points of zero growth for average humidity varied between genotypes, with values of about 67.3% for genotype 104, 66.4% for genotype A1, 59.5% for genotype P2, and 62.7% for genotype 143. Regarding the photoperiod, the minimum growth point varied between genotypes, with values of about 10.8 for genotype 104, 10.8 for genotype A1, 10.2 for genotype P2, and 10.4 for genotype 143.

The genotypes presented relatively high growth rates during spring and summer (Figure 7). Genotypes 104, A1, and 143 presented the greatest growth in the spring season, followed by the summer season, with no significant differences in OGR between winter and autumn (Figure 7A). Genotype P2 had greater growth in spring and summer, followed by autumn and winter, with no differences between the last two periods.

In winter, no significant differences were detected between genotypes (Figure 7A). In spring, genotype A1 presented the highest OGR (11.8 cm), whereas the other genotypes did not differ significantly. In summer, the P2 genotype presented the highest OGR (9 cm) (Figure 7A). In autumn, the highest rates were observed for genotypes A1 (2.8 cm) and P2 (4.4 cm), whereas the rates for genotypes 104 (0.3 cm) and 143 (1.1 cm) did not differ significantly.

For the PNR variable, the highest growth rates occurred in spring and summer. In spring, genotype P2 presented the lowest value (Figure 7B), whereas the other genotypes did not differ significantly. In winter, summer, and autumn, no significant differences were detected between the genotypes.

Among all genotypes, spring presented the highest PGR rates. When evaluating genotypes within the season, in spring, A1 had the greatest growth (20 cm), whereas, in summer, A1

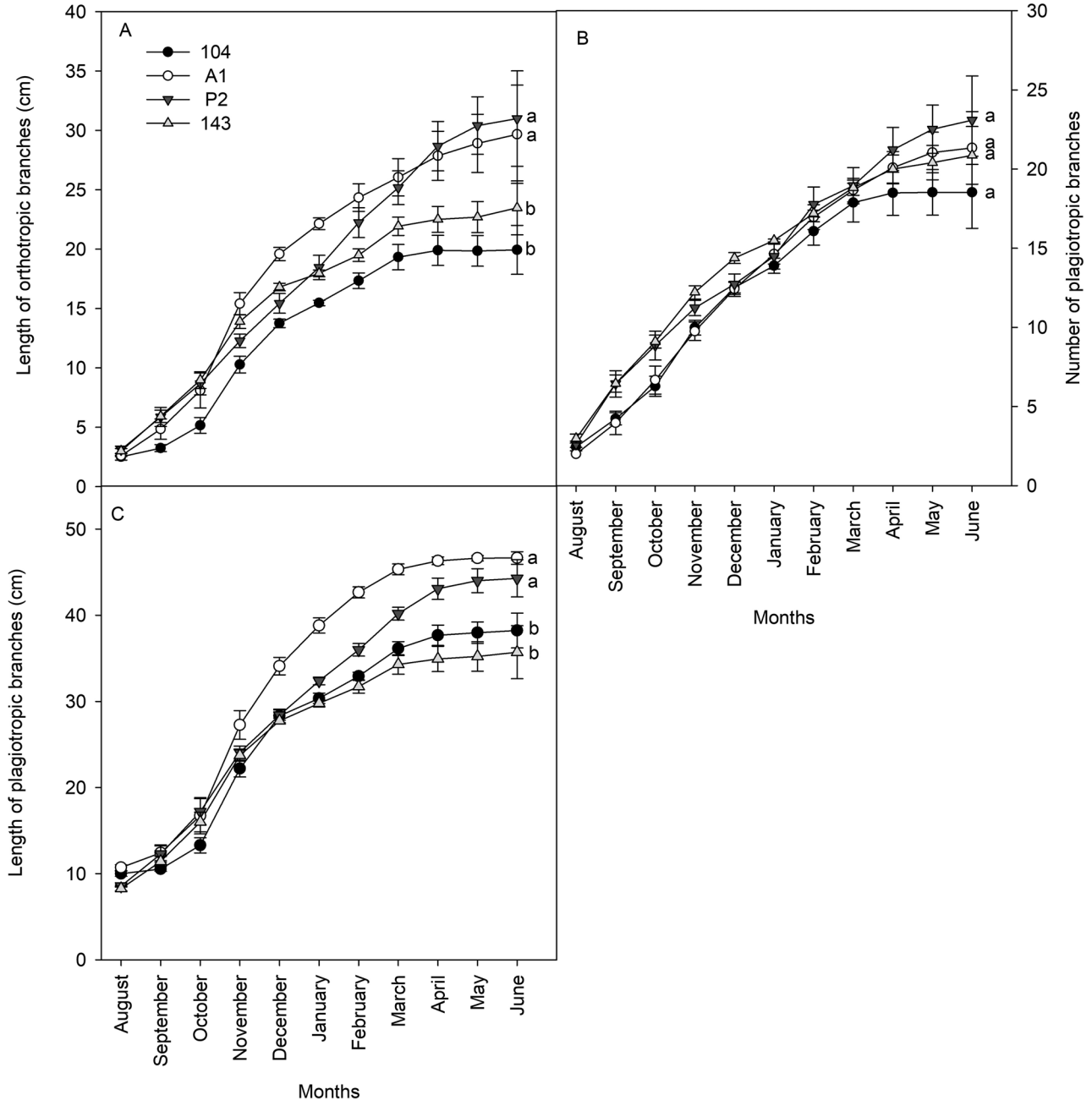

FIGURE 5 Length of orthotropic branches (cm), length of plagiotropic branches (cm), and number of plagiotropic branches of early-maturing genotypes 104 and A1, intermediate P2, and late 143. Mean values followed by the same lowercase letter do not differ significantly, as determined by the Scott–Knott test ($p < 0.05$). Error bars indicate the standard deviation from the mean.

(10.43 cm) and P2 (11.09 cm) had the highest growth rates; in autumn and winter, the genotypes did not differ from each other (Figure 7C).

The set of meteorological data and morphological rates of the four genotypes in the seasons of the year was considered. Significant positive coefficients greater than 0.500 were observed between the growth variables OGR, PNR, and PGR and the meteorological variables minimum temperature, precipitation, humidity, photoperiod, and Etp ($p < 0.05$). Maximum temperature and radiation had a low negative correlation with OGR and PGR and a low positive correlation with PNR. The mean temperatures also had low positive correlations (Table 3).

PCA showed that 88% of the total variability in the data was explained by Principal Component 1 and Principal Component 2 (Figure 8). The meteorological and growth variables exhibited a seasonal distribution and were grouped into winter–autumn and spring–summer according to the proximity of the growth variables to precipitation, humidity, and photoperiod in spring.

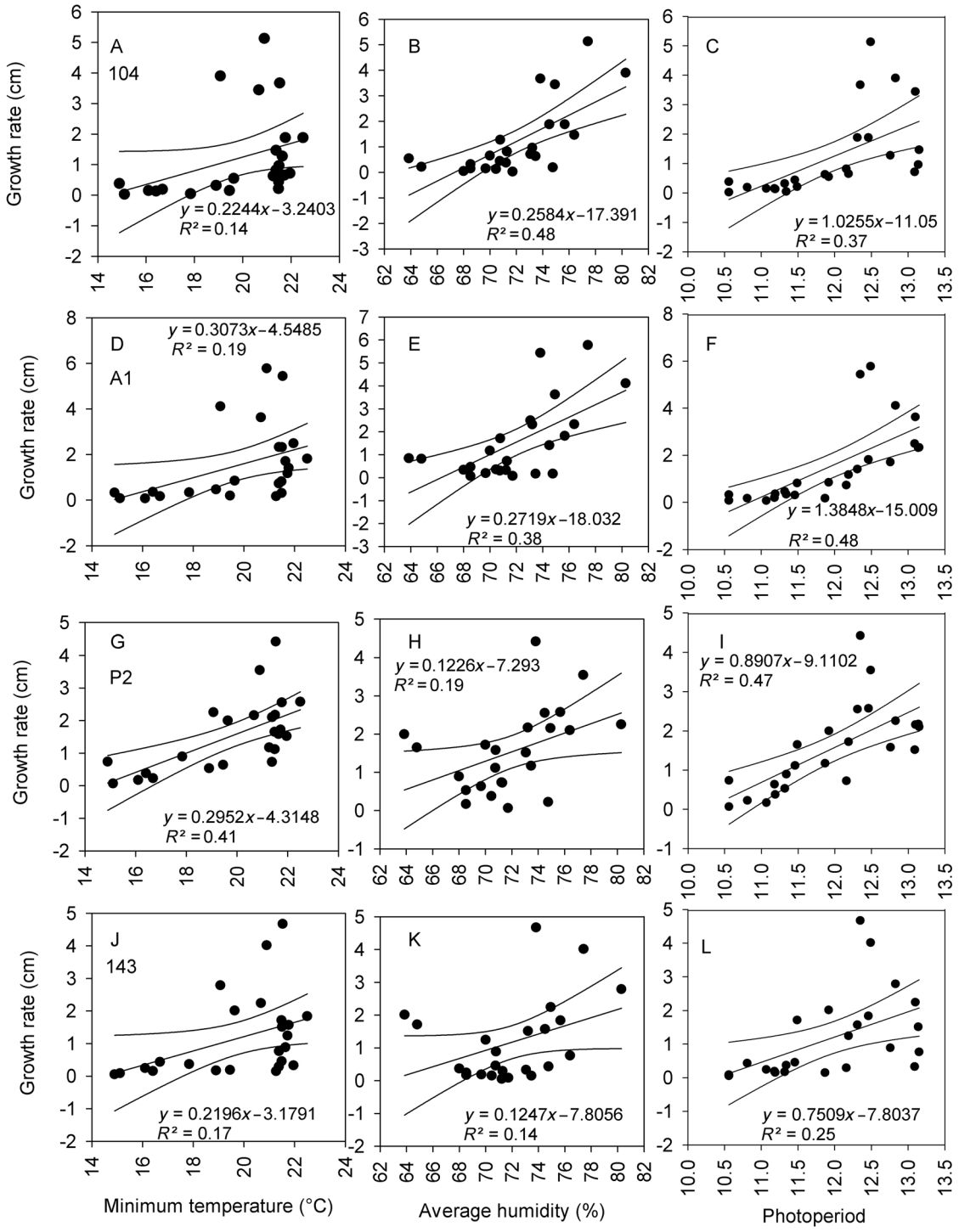

FIGURE 6 Linear regression graphs of the relationships among three meteorological variables, minimum temperature, average humidity, and photoperiod growth of plagiotropic branches, considering the biweekly evaluation rates of early-maturing genotypes 104 (A–C) and A1 (D–F), intermediate P2 (G–I) and late 143 (J–L).

4 | DISCUSSION

The blooms occurred between July and October and between February and May of the following year, with greater occurrence in periods with photoperiods less than 12 h. Recent studies on *C. canephora* indicated that the induction process can begin in February and last until October; in such cases, floral transcription peaks in June, which coincides with the shorter photoperiod and colder temperatures typical of winter in coffee regions in Brazil (Cardon et al., 2022). Ricci et al.

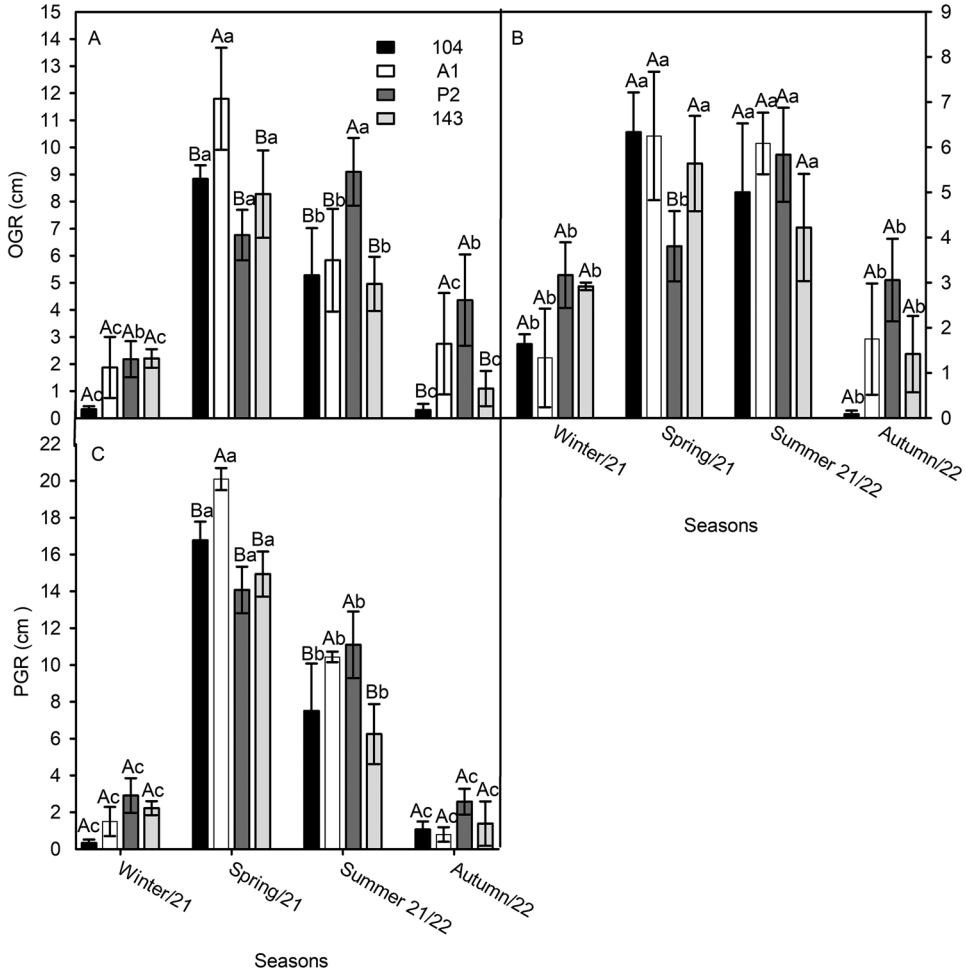

FIGURE 7 (A) Orthotropic branch growth rate (OGR; cm), (B) plagiotropic branch growth rate (PGR; cm), and (C) plagiotropic branch number rate (PNR) of early-maturing genotypes 104 and A1, intermediate P2, and late 143. The mean values followed by the same uppercase letter of genotypes within a season and a lowercase letter between seasons within each genotype level do not differ significantly, as determined by the Scott–Knott test ($p \leq 0.05$). The bars indicate the standard deviation from the mean.

TABLE 3 Pearson correlation coefficients between growth rates and climate during the four seasons of the year.

Variables	Max. T.	Min. T.	Avg. T.	Precipitation	Radiation	Photoperiod	Etp	Hum.
OGR	−0.027	0.739*	0.153	0.780*	−0.019	0.831*	0.552*	0.801*
PNR	0.169	0.840*	0.393	0.834*	0.248	0.882*	0.732*	0.707*
PGR	−0.177	0.724*	0.159	0.763*	−0.133	0.859*	0.507*	0.810*

Abbreviations: Avg. T., average temperature; Etp, potential evapotranspiration; Hum., humidity; Max. T., maximum temperature; Min. T., minimum temperature; OGR, orthotropic branch growth rate; PGR, plagiotropic branch growth rate; PNR, plagiotropic branch number rate.
*denotes significance at $p < 0.05$.

(2013), when studying *C. canephora*, also reported flowering in October. This expansion of the time window explains the occurrence of asynchronous flowering, in which the development of floral buds begins at different times until anthesis. Moreover, a few variations in transcription factors, which negatively regulate flowering, exist throughout the year (Cardon et al., 2022).

The blooms in February and May appear to follow a chronological sequence according to bud formation, suggesting a relationship between bud development and the timing of flowering. Genetic material plays a role in the induction season, as it was possible to observe the buds already induced on the growth branches in different months, from March to July. In regions with photoperiods of less than 13 h, the floral

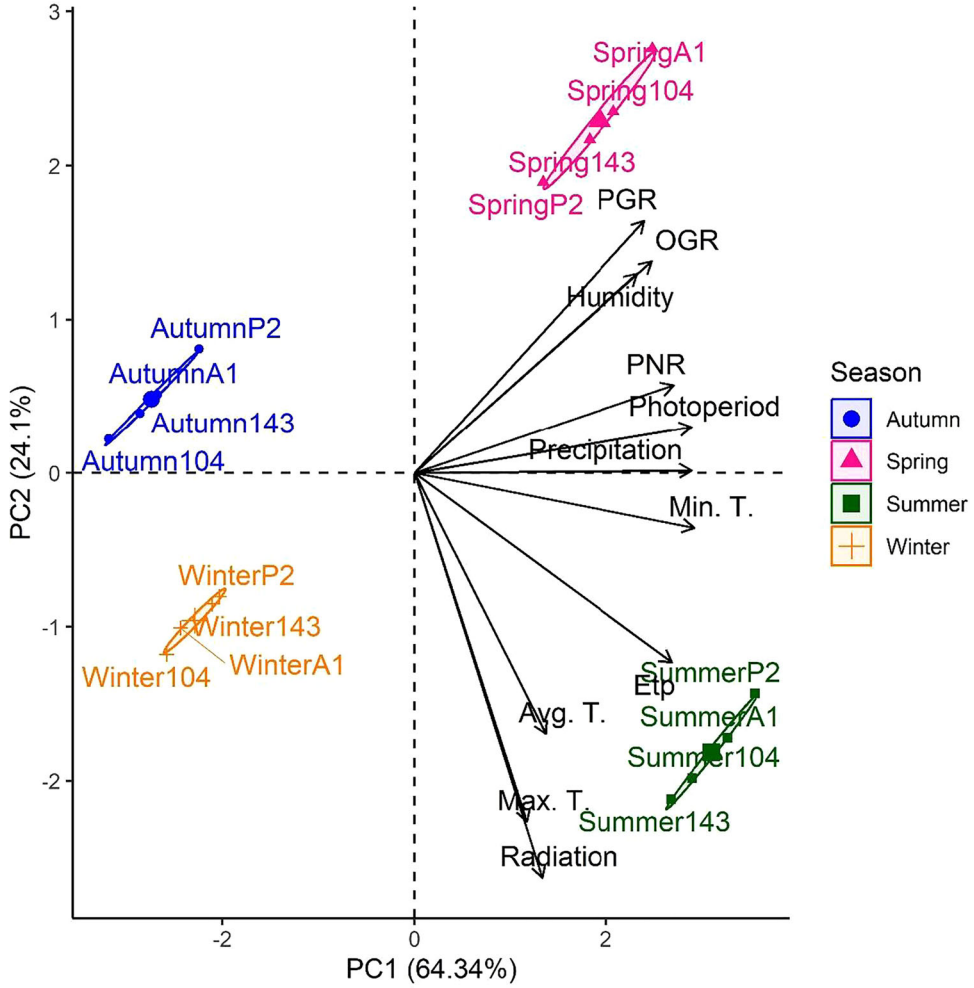

FIGURE 8 A principal component analysis (PCA) score chart is shown, in which the 11 factors analyzed in the four seasons were considered. These parameters correspond to the orthotropic branch growth rate (OGR), plagiotropic branch number rate (PNR), plagiotropic branch growth rate (PGR), maximum temperature (Max. T.), minimum temperature (Min. T.), average temperature (Avg. T.), precipitation, humidity, radiation, photoperiod, and potential evapotranspiration (Etp). PC1, Principal Component; PC2, Principal Component 2.

induction of coffee plants may be more related to temperature variations and water deficit (Ramírez et al., 2010). The CaFT1 protein in *C. canephora* is upregulated by cold and even drought (Cardon et al., 2022).

Full flowering occurred in September, 9 days after the first rains, which was also reported by Gomez et al. (2016). Precipitation is essential for the coffee flowering process, which is characterized by anthesis and occurs due to an increase in ethylene (Ságio et al., 2014). After anthesis in September, florigen expression decreases rapidly, followed by the vegetative growth of new branches, which marks the restart of the cycle (Cardon et al., 2022).

However, the presence of sporadic rains and the increase in minimum temperature in the dry season are factors that influence the flowering periods of *C. canephora*, which can bring forward or delay the flowering season (Kath et al., 2023). As a result, genotypes such as A1 flower and ripen fruits in a desynchronized manner. The high productive potential of the A1 genotype is widely recognized by producers, and its flowering is distributed over successive flowerings. This pattern may be a mechanism to reduce the proportion of reproductive structures exposed to climatic extremes. Kath et al. (2023) found that the early flowering of *C. canephora* is favored by high minimum temperatures and a reduction in the amount of precipitation.

After flowering, the pellet formation and fruit expansion phase occurs, which is a critical period for the development of coffee plantations. The highest rates of accumulation of dry matter in fruits occur in these phases, especially after the fourth month of flowering (Covre et al., 2022). These phenological phases are favored by the abundant rains in spring and summer. The green grain stage is prolonged because of grain hardening. On the other hand, the subsequent stage, known as cane green, is the shortest, lasting stage (just a few weeks). It occurs immediately after the fruits become cherries.

4.1 | Production

The maturation and harvest period varies between genetic materials of *C. canephora*, where early varieties take 34 weeks (harvest in May), intermediate varieties take 41 weeks (harvest in June), and late varieties take 45 weeks (harvest in July) (Bragança et al., 2001). In this study, a significant delay of up to 8 weeks was observed in early varieties. Harvesting was performed over 39 weeks for genotype 104 and up to 42 weeks for A1. These findings suggested that early genotypes are more prone to a delay in their maturation cycle because of environmental conditions and genetic characteristics.

In the Philippines, where the average temperature is 27.6°C, researchers have recorded 40 weeks from anthesis to ripening of robusta coffee (Salazar et al., 2019). In contrast, in Brazil, a study conducted by Crasque et al. (2024) under meteorological conditions similar to those of this study revealed that, for early-maturing genotypes, maximum physiological maturity occurs at about 35 weeks, whereas for late-maturing genotypes, this period extends to about 47 weeks, with an index of maturity greater than 80%.

Our results highlighted the importance of the maturation stage in obtaining a relatively high yield. Different coffee genotypes can respond differently to different environmental conditions (Venancio et al., 2020). The significant presence of green grains in certain genotypes suggests challenges during the maturation and flowering processes. Both environmental and genetic factors play a key role in coffee production (Gaspari-Pezzopane et al., 2004; Venancio et al., 2020). Therefore, genetic characteristics significantly affect productivity, as evidenced by genotype A1, which demands more ripe fruits, whereas genotype 143 has a high yield, which was also reported by Partelli et al. (2021).

Additionally, during processing, some components of the fruit are discarded, forming a "coffee husk," while the endosperm is retained, as it is the commercially sold part. The variation in the percentage of seed weight per fruit among genotypes indicates differences in biomass allocation (Partelli et al., 2021).

These results highlighted the importance of careful selection of genotypes suited to local conditions and management practices that aim to optimize the maturation and harvesting process to produce high-quality coffee with satisfactory yields.

4.2 | Growth variables

Between July and August, a period of rest was found regarding the development of the aerial part, when the plants emitted one or two pairs of small leaves, which delimits the phenological years, and in these buds, February flowering was observed. During this same period, a shorter photoperiod and minimal branch growth were observed, with the P2 genotype having fewer restrictions on photoperiod, minimum temperature, and humidity than the other genotypes.

The leaf bud formation phase occurs from September to March, when days are long, with 12 h or more of effective light, as also observed for *C. canephora* (Dubberstein et al., 2017; Partelli et al., 2013; Solimões et al., 2023).

The photoperiod may not be an important determinant for the development of the aerial part, which naturally grows under photoperiods close to 12 h/12 h with few seasonal variations (Cardon et al., 2022; Djerrab et al., 2021). The highest growth rates were recorded in the rainy season, with an emphasis on October and November, a period in which the grains are in the initial stage of formation or beginning to expand. The subsequent slowdown in growth from October onward can be attributed to competition between vegetative and reproductive organs, as fruit development implies an intense demand for photoassimilates (Covre et al., 2022).

Genotypes A1 and P2 showed the highest vegetative vigor, with P2 presenting a longer growth cycle. These genotypes have been studied because of their greater vegetative vigor (Covre, Canal, et al., 2016) and important root characteristics for breeding programs (L. O. E. Silva, Schmidt, et al., 2020).

Correlation and PCA suggested that, in general, spring season conditions, such as minimum temperatures, precipitation, photoperiod, and humidity, are most strongly associated with increases in plant growth and development rates. The precipitation was adequate, considering that the minimum average in the state of Espírito Santo was close to 1000 mm, as observed by Venancio et al. (2020).

Plant growth may be influenced by temperature, but significant variation was found in the data that was not explained by the regression line. The minimum temperature that most restricted growth was between 16.6°C and 17.8°C, and the average minimum temperature above 20°C between September and March increased during the growth phase. According to Partelli et al. (2010, 2013), when temperatures drop below 17°C, the growth rate of branches decreases, whereas temperatures ranging between 21°C and 27.5°C are ideal for the satisfactory growth of *C. canephora*. Covre, Partelli, et al. (2016) reported that the growth rate of *C. canephora* branches was not limited by the minimum average temperature. Until the end of the 20th century, *C. canephora*-growing regions were vulnerable to cold night temperatures, especially during the flowering season (Richardson et al., 2023). However, these risk factors have become less frequent since then, being replaced by higher minimum temperatures during the growing season (Richardson et al., 2023).

Although the negative correlation between maximum temperatures, solar radiation, and growth rates of orthotropic and plagiotropic branches is low, under high temperatures and increased radiation exposure, the growth of these

characteristics decreases. Extreme temperatures restrict development and harm production (Dubberstein et al., 2017; Kath et al., 2020). Water deficit associated with high temperatures and irradiance is the environmental condition that affects crops the most, as reported by Venancio et al. (2020) in the Espírito Santo region. In summer, there is a combined effect of drought, heat, and irradiance that affects growth and productivity.

Moisture plays a key role in vegetative growth. Although the critical point showed a small variation between genotypes, humidity is more important for early genotypes, and the P2 genotype has a lower sensitivity, confirming the hypothesis supported by the study by Kath et al. (2023).

Therefore, these climatic data need to be integrated to understand the interactions that regulate the growth of branches of the coffee tree *C. canephora*. Continuous climate monitoring systems and statistical analyses can provide advanced information to producers, allowing adjustments in agricultural practices, such as control, security, and fertilization, to improve branch development and, consequently, coffee production. This approach, which considers different climatic elements, contributes to the sustainable advancement of coffee farming.

5 | CONCLUSIONS

The analysis of flowering events that occurred between July and October 2021, as well as between February and May 2022, suggests a relationship between the chronological sequence of flowering and the formation of branch nodes. The early-maturing genotypes presented earlier flowering, characterized as medium flowering, than the intermediate- and late-maturing genotypes.

Clone A1 was more sensitive to climate variations, resulting in a significantly greater number of blooms than the other clones. On the other hand, late clone 143 achieved the highest yield, with a greater quantity of fruits reaching the cherry ripening stage.

Genotypes A1 and P2 exhibited greater growth, especially during spring and summer, that is, periods characterized by an increase in plant growth and development rates, which was associated mainly with greater precipitation. Additionally, early clones were more susceptible to wetter conditions, higher minimum temperatures, and longer photoperiods than other clones.

AUTHOR CONTRIBUTIONS

Jeane Crasque: Data curation; formal analysis; writing—original draft; writing—review and editing. **Marcone Comério**: Investigation; methodology; validation. **Paulo Sérgio Volpi**: Investigation; methodology. **Lúcio de Oliveira Arantes**: Methodology; resources. **Edilson Romais Schmildt**: Methodology; validation; writing—review and editing. **José Altino Machado Filho**: Resources. **Thiago Corrêa de Souza**: Validation; writing—review and editing. **Sara Dousseau-Arantes**: Conceptualization; methodology; project administration; resources; supervision; validation; writing—review and editing.

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