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Application of Double Sigmoid Logistic Models to the Growth of Three Cut Rose Varieties

Aplicación de modelos logísticos doble sigmoide en el crecimiento de tres variedades de rosa de corte

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ABSTRACT

Roses are flowers widely accepted worldwide. Colombia successfully produces rose stems for cutting due to its multiple favorable microclimates. However, meeting international market quality standards requires a rigorous cultivation program, for which growth models are a novel tool that enables a more precise definition of phenological stages. In this work, the application of double-sigmoid logistic models was evaluated in relation to the growth of three cut rose varieties, i.e., Freedom, Pink Floyd, and Mondial, which were cultivated in soil under plastic cover. A completely randomized design was implemented, with three treatments corresponding to the three varieties. Respectively, Mondial, Pink Floyd, and Freedom required 84.1, 82.6, and 77.4 days for their floral button to develop, as well as different thermal times to reach each phenological stage. The total chlorophyll content increased until the end of the harvest cycle, reaching 64.7, 65.5, and 71.8 for Mondial, Pink Floyd, and Freedom. The earliest variety was the latter, which needed only 1134 growing degree days, while the latest variety was Mondial with 1233. The Freedom variety exhibited the highest floral button diameter and length. The increase in the diameter and length of the floral button followed a simple sigmoid pattern, while the stem diameter fit a double sigmoid pattern.

Keywords: thermal time, Rosaceae, floral button, SPAD, flowers, phenology

RESUMEN

Las rosas son flores con amplia aceptación a nivel mundial. Colombia produce con éxito tallos de rosa para corte gracias a sus múltiples microclimas favorables. Sin embargo, cumplir con los estándares de calidad del mercado internacional requiere un programa de cultivo riguroso, para lo cual los modelos de crecimiento constituyen una herramienta novedosa que permite definir las etapas fenológicas con mayor precisión. En este trabajo se evaluó la aplicación de modelos logísticos de doble sigmoide respecto al crecimiento de tres variedades de rosa de corte, i.e., Freedom, Pink Floyd y Mondial, las cuales fueron cultivadas en suelo bajo cobertura plástica. Se implementó un diseño completamente al azar, con tres tratamientos correspondientes a las tres variedades. Respectivamente, Mondial, Pink Floyd y Freedom requirieron 84.1, 82.6 y 77.4 días para el desarrollo del botón floral, así como diferentes tiempos térmicos para alcanzar cada etapa fenológica. El contenido total de clorofila aumentó hasta el final del ciclo de cosecha, alcanzando valores de 64.7, 65.5 y 71.8 para Mondial, Pink Floyd y Freedom. La variedad más temprana fue esta última, que requirió únicamente 1134 grados-día de crecimiento, mientras que la más tardía fue Mondial con 1233. La variedad Freedom presentó los mayores valores de diámetro y longitud del botón floral. El incremento en el diámetro y la longitud del botón floral siguió un patrón sigmoide simple. Entretanto, el diámetro del tallo se ajustó a un patrón sigmoide doble.

Palabras clave: tiempo térmico, Rosaceae, botón floral, SPAD, flores, fenología

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Introduction

Roses are one of the most popular flowers in the international market and were the leading global export in 2022 from the Netherlands, Ecuador, Kenya, Colombia, and Ethiopia [1]. Colombia has remained at the forefront of cut rose production for the last 50 years, thanks to its multiple favorable microclimates. As a result, roses are the country's most exported flower, accounting for 23% of the total flower export market [2].

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The production of rose stems for cutting requires temperatures between 15 and 30 °C. However, when these temperatures are exceeded, growth is adversely affected, leading to the appearance of small, pale flowers with fewer petals. Conversely, temperatures below 5 °C promote changes in anthocyanin production, affecting petal pigmentation and resulting in short, thin, and small stems [3], which ultimately affects quality. Furthermore, rose producers face significant challenges due to the increasing diversification and differentiation of products, with increasing market demands in terms of quality, volume, and frequency of delivery during specific seasons (*e.g.*, Mother's Day, Valentine's Day, International Women's Day, Christmas, and Saint George's Day in Spain). This pressure on production has become a critical factor in the commercialization of flowers [4].

To meet the market's high demands, a more rigorous cultivation program is required. Growth models are a novel tool that estimate plant growth based on various climate and soil conditions, enabling the mathematical representation of the crop production process. This facilitates labor planning (pruning, fertilization, irrigation, and pest and disease control) and improves crop yield [5]. The use of double sigmoid logistic models has shown a better fit than other models in estimating crop growth parameters, such as stem length in pink 'snowflake' roses [6], plant height in rice [7], fruit diameter in nectarines [8] and blackberries [9], fresh mass in coffee fruits [10], and dry mass in canola plants (*Brassica napus* L.) [11].

Additionally, to implement an appropriate harvesting program, it is necessary to identify the different phenological stages of cultivation, which involves monitoring the appearance, growth, and development of the plant's vegetative and reproductive structures as influenced by biotic and abiotic factors [12]. Since temperature variation greatly influences crop phenology, it is necessary to quantify the cumulative growing degree days (CGDD), as plant biomass generation correlates linearly with temperature. This is leveraged to adjust mathematical models based on physiological time, thereby determining the energy demand [13], which allows producers to estimate crop yields based on the CGDD for each region [14].

In light of the above, this study aims to evaluate the application of double sigmoid logistic models in the growth of three cut rose varieties, *i.e.*, Freedom, Pink Floyd, and Mondial, cultivated in soil under winter conditions in the municipality of Toca, Boyacá, Colombia.

Materials and methods

Location

This study was carried out during the winter on a farm in the municipality of Toca, located at 5° 34′ 44″ N, 73° 12′ 17′′ W, at an altitude of 2687 m. The average minimum and maximum temperatures recorded during our work were 9 and 32 °C, respectively, with a relative humidity of 42%.

Plant material

We used floral stems from rose plants of the Freedom, Pink Floyd, and Mondial varieties, which were grafted onto the Natal Brier rootstock. The plants were five years old and established directly in soil with a pH of 6.8, an electrical conductivity of 1.91 dS m^{-1}, and concentrations of 11.6, 31.3, 664.8, 544, 1962, and 463 mg kg^{-1} of NH_4^+, NO_3^-, P, K^+, Ca^{2+}, and Mg^{2+}, respectively, along with 2.3% organic matter. The evaluated beds were placed in the same block and underwent similar cultivation practices. However, phytosanitary management differed for the Mondial and Freedom varieties, which were susceptible to *Peronospora sparsa* and *Sphaerotheca pannosa*, respectively. Weekly monitoring was conducted to diagnose the state of the crop. Fertilization consisted of two weekly drip irrigations and one hose irrigation, totaling a weekly flow of 800 to 900 L per bed. This process also included the application of 149, 21, 55, 150, 85, 55, 44, 0.80, 1.50, 0.25, 0.30, 0.30, and 0.10 mg L^{-1} of NO_3^-, NH_4^+, P_2O_5, K^+, Ca^{2+}, Mg^{2+}, S, Fe, Mn, Cu, Zn, B, and Mo, respectively.

Among the cultivation practices, sanitary pruning was performed to remove basal shoots, diseased stems, and other unproductive stems. Flowers with weak, damaged, or twisted stems were also removed. On productive stems, debuttoning was performed, a process that involves removing the axillary shoots from a productive stem bearing a flower in order to stimulate apical dominance.

Cuts for the production program were made at a 0.5 cm angle from the production area on stems with a 0.8 cm diameter. We cut 50 stems at the third node using pruning knives (Zubi Hello, Colombia) that had been previously disinfected with 1% sodium hypochlorite in order to prevent disease spread.

Experimental design

A completely randomized design was implemented, with three treatments corresponding to the analyzed varieties. Each treatment had five replicates, for a total of 15 experimental units (with ten stems per unit) and 150 stems evaluated.

Response variables

Once 50 stems of each variety had been marked, daily monitoring began to determine the days to sprouting, counting the days until the sprout reached 0.5 cm. The time elapsed (in days) from the cut to each phenological stage was then determined for each variety. The following stages were recorded: rice button (RB, equatorial stem diameter<0.5 cm), pea button (PB, equatorial diameter of 0.5-0.8 cm), chickpea button (CB, equatorial diameter of 0.8-1.2 cm), ball button (BB, equatorial stem diameter>1.2 cm before petal

visualization through sepal separation), color striped button (CSB, when the sepals separate, revealing the petals), and harvest point button (HPB, the stage at which the flower is typically cut for commercial maturity, not physiological maturity) [15]. To evaluate crop growth, the CGDD were calculated for each phenological stage, as shown in Eq. (1).

$$CGDD = \sum_{i=1}^{n} \frac{T_{\max} - T_{\min}}{2} - T_{base} \quad (1)$$

where Tmax and Tmin are the maximum and minimum daily temperatures, respectively, and Tbase is the base temperature (5.3 °C) [15].

In each stem, measurements were taken three times a week until all phenological stages were completed (button at harvest time). The stem length (SL, cm) was measured using a tape measure from the appearance of the first true leaf to the harvest, with the base of the sprouted button as the starting point. The stem diameter (SD) was also measured simultaneously with SL, with measurements taken at the base and the middle of the stem to obtain an average diameter in centimeters. The flower button length (BL) and the flower button diameter (BD) were measured from the appearance of the first stage (rice button) until the harvesting of stems (button at harvest time). This was done using a Mitutoyo digital caliper (Mitutoyo Corporation, Japan) with a precision of 0.05 mm.

The total chlorophyll (TC) content was measured indirectly using a SPAD-502 Plus (Konica Minolta Inc., Japan), whose measurements allowed for *in situ* estimations [16]. Readings were taken from the first true leaf on the floral stem in the basal, middle, and apical parts of the leaves. Two readings were made per week.

The measurements of SL, SD, BL, and BD for each variety were fitted to a double-sigmoid logistic model, as shown in Eq. (2), which provides a strong fit for plant growth parameters [7].

$$f(t) = \frac{\alpha}{1 + e^{-(b+ct+dt^2+et^3)}} \quad (2)$$

where f(t) is the time-dependent growth variable; α is the maximum value reached by the variable over time; and b, c, d, and e are constants related to the inflection points and relative slopes of the model. This equation was derived to obtain the growth rate curves for the parameters, expressed in centimeters per growing degree day (GDD). The second derivative of Eq. (2) was set to 0 in order to identify the points where the slope was 0, thereby establishing the model's maximum growth points. These points correspond to the CGDDs at which the model exhibits inflection points, indicating changes in the phenological stages of cut rose growth.

Data analysis

A test of homogeneity of variances was performed across the data from the different varieties, and a Kolmogorov-Smirnov normality test was used to assess the assumptions of the analysis of variance (ANOVA). Subsequently, a 5% Tukey treatment comparison test was performed. Data analysis was carried out using SAS OnDemand for Academics (SAS Institute Inc., Cary, NC).

Results and discussion

Days to flowering

Significant differences were observed across the different floral phenological stages (PB, CB, BB, and CSB). However, no significant differences were observed for the first (RB) and last (HPB) stages (Table I). The earliest rose variety, which required the least thermal time to reach flowering, was Freedom, accumulating 1134 CGDD, while the latest variety was Mondial, with 1233 CGDD. During the vegetative phase, CGDD accumulation from the initial cut to reach the RB stage accounted for 53.2, 52.55, and 50.34% of the total for the Mondial, Pink Floyd, and Freedom varieties, respectively. This is similar to the findings of [15], who reported that approximately 50% of the thermal accumulation is needed for the vegetative period and another 50% for the reproductive period.

In this context, [17] mention that temperature influences floral development during the period from visible buttoning to flowering. In the commercial production of roses in greenhouses, any reduction in temperature during that period can increase the size of the rose flower buttons. However, while low temperatures delay flowering in cut roses, they improve the flower's final quality. Similarly, [15] have stated that temperature affects the number of sepals and the occurrence of malformed flowers. It should be noted that the greenhouse used for this study had the curtains closed. According to [15], this condition reduces the harvest time. In contrast, when the curtains are continuously opened and closed, the harvest time is extended due to lower temperatures and relative humidity.

Total chlorophyll (TC)

Significant differences were observed in TC from the first measurement at 26 days after the cut (DAC), up to 54 DAC. From that point onward, no significant differences were observed between the three varieties (Fig. 1). TC showed an increasing trend from the beginning of the floral cycle until the Mondial and Pink Floyd varieties reached the CB stage, and the Freedom variety reached the BB stage. Afterwards, TC remained constant until harvest from the mid-BB stage for Mondial and Pink Floyd and the CSB stage for Freedom. This suggests that the latter accumulates a greater amount of TC, likely because it is the earliest variety. Additionally, this variety may require higher nitrogen nutrition. [18] state that the chlorophyll content is related

Table I. Days to flowering and thermal time required to reach each of the phenological stages of three rose varieties

Time (DAC)							
Variety	**S**	**RB**	**PB**	**CB**	**BB**	**CSB**	**HPB**
Mondial	11.06[a]	46.2[a]	51.73[a]	56.98[a]	61.43[a]	73.06[a]	84.10[a]
Pink Floyd	11.51[a]	44.92[a]	50.17[a]	55.37[a]	61.10[a]	68.58[ab]	82.64[a]
Freedom	10.26[a]	40.70[b]	45.04[b]	50.06[b]	54.91[b]	63.35[b]	77.48[a]
LSD of Tukey	1.30	2.98	3.79	4.99	4.60	6.72	6.82
Thermal time (CGDD)							
Variety	**S**	**RB**	**PB**	**CB**	**BB**	**CSB**	**HPB**
Mondial	135.37[a]	656.86[a]	742.71[a]	821.70[a]	889.65[a]	1 067.77[a]	1 233.34[a]
Pink Floyd	137.92[a]	636.77[a]	719.39[a]	793.17[a]	884.43[a]	997.52[ab]	1 211.66[a]
Freedom	122.26[a]	571.02[b]	638.79[b]	715.93[b]	790.89[b]	914.87[b]	1 134.31[a]
LSD of Tukey	23.56	45.39	58.24	72.24	72.04	104.63	107.40

Note: S: sprouting; RB: rice button; PB: pea button; CB: chickpea button; BB: ball button; CSB: color striped button; HPB: harvest point button; DAC: days after cut; CGDD: cumulative growth degree days. LSD: least significant difference. Means with different letters in the same column indicate significant differences between varieties according to the Tukey mean test ($p \leq 0.05$).
Source: Authors

to plant photosynthesis, the crop's phenological stage, and the nitrogen content. Therefore, knowing the TC content is important in determining the appropriate amount and timing of fertilization.

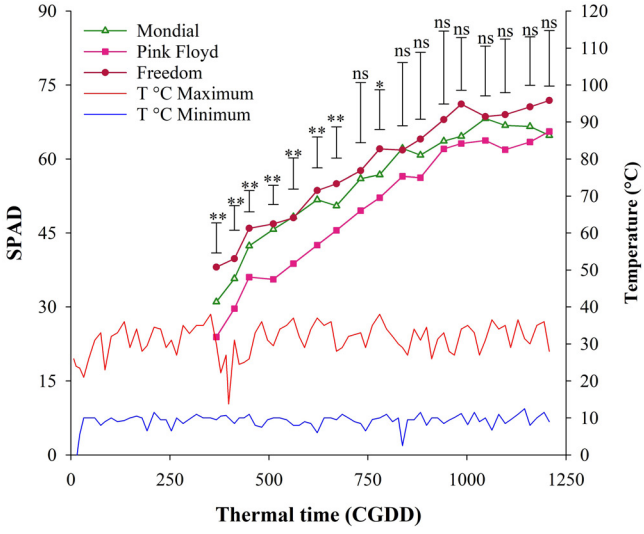
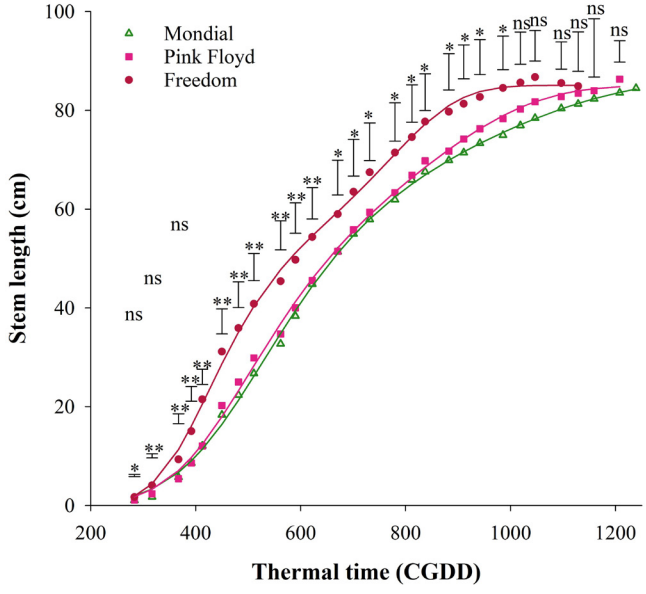


Figure 1. Indirect estimation of total chlorophyll content from special products analysis division (SPAD) units for three rose varieties
Note: The vertical bars indicate significant differences according to the Tukey test ($p \leq 0.05$). ns: no differences; * and **: statistical differences at 5 and 1%, respectively.
Source: Authors

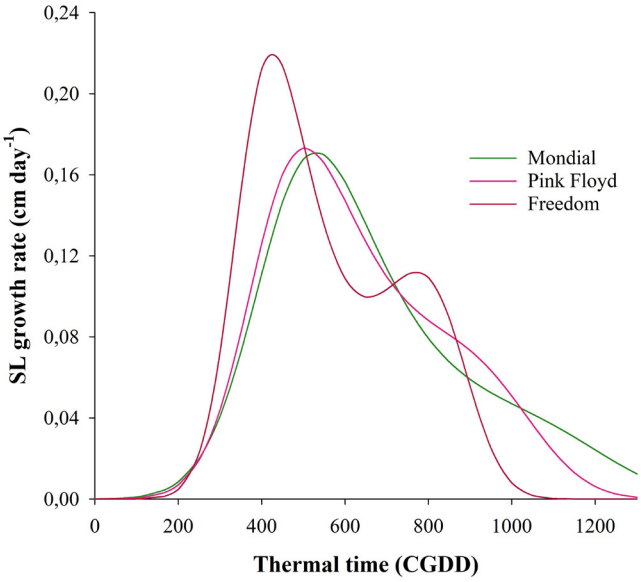
Stem length (SL)

Significant differences in SL were observed among the three rose varieties evaluated at all measurement times, except on day 70 after cutting. The Freedom variety exhibited the highest SL, with a value of 1.68 cm at 21 DAC (283.3 CGDD), followed by Pink Floyd and Mondial with 0.98 and 0.95 cm, respectively. This pattern was consistent throughout the growth phase until 70 DAC (1018.8 CGDD). Here, the SL values were 85.6 cm for Freedom, 80.3 cm for Pink Floyd, and 76.9 cm for Mondial (Fig. 2, Table I).

When analyzing the SL of the Mondial variety over time, a sigmoidal growth pattern was evidenced. Initially, a slow growth was observed until 23 DAC (316.9 CGDD). The growth rate then increased until 37 DAC (510.9 CGDD). Thereafter, the acceleration intensified until 44 DAC (622.2 CGDD) as the rose plant approached the first flowering stage—corresponding to RB. From this point until 58 DAC (837.3 CGDD), SL growth slowed considerably, coinciding with the period between the PB stage and the beginning of CB. Afterwards, a phase of slow stem growth continued until 84 DAC (1239.2 CGDD), corresponding to HPB, at which point the stems reached 84.5 cm in length.



(a)



(b)

Figure 2. Fitting the double sigmoid logistic model to a) the growth and b) the growth rate of the stem length of roses of the Mondial, Pink Floyd, and Freedom varieties
Note: The vertical bars indicate significant differences according to the Tukey test ($p \leq 0.05$). ns: no differences; * and **: statistical differences at 5 and 1%, respectively.
Source: Authors

For the Pink Floyd variety, growth began slowly until 23 DAC (316.9 CGDD). From there, growth accelerated until 45 DAC (622.2 CGDD), when the plant was at the onset of the RB stage. The growth rate then continued to decelerate as the flower button progressed through each of the different phenological stages. When the button approached CSB, growth stabilized markedly until HPB was reached at 82 DAC (1208 CGDD), with a final SL of 86.3 cm.

The SL of the Freedom variety grew more slowly than the other varieties until 23 DAC (316.9 CGDD). Thereafter, SL increased more rapidly than in the other varieties until 37 DAC (510.9 CGDD). At this time, a slight deceleration occurred, coinciding with the stem entering the RB flowering stage, which continued until 58 DAC (837.3 CGDD). Afterward, growth remained constant until harvest at 77 DAC (1128.9 CGDD), reaching a final SL of 84.9 cm. These values are similar to those reported by [19], who found SL values ranging from 77 to 88 cm across different irrigation levels for the Freedom variety.

The derivative of the model (Fig. 2b) showed that, for Mondial and Pink Floyd, there was only one maximum growth rate (0.1710 and 0.1740 cm GDD^{-1}) at 531 and 505 CGDD, respectively, coinciding with the onset of floral button formation, followed by a decrease throughout the cutting cycle. This suggests that a simple sigmoid logistic model can describe this variable, similar to the model described by [20], who found a great fit of the Gompertz simple sigmoid model for the cumulative number of harvested stems. In contrast, for Freedom, the derivative indicated two maxima (fitting a double sigmoid logistic model) in growth rate (0.2195 and 0.1125 cm GDD^{-1}) at 425 and 773 CGDD, corresponding to the beginning of flower button formation and the start of BB, respectively. Additionally, a minimum of 0.0990 cm GDD^{-1} was recorded at 656 CGDD (between PB and CB), indicating an SL decrease in preparation for flower button development.

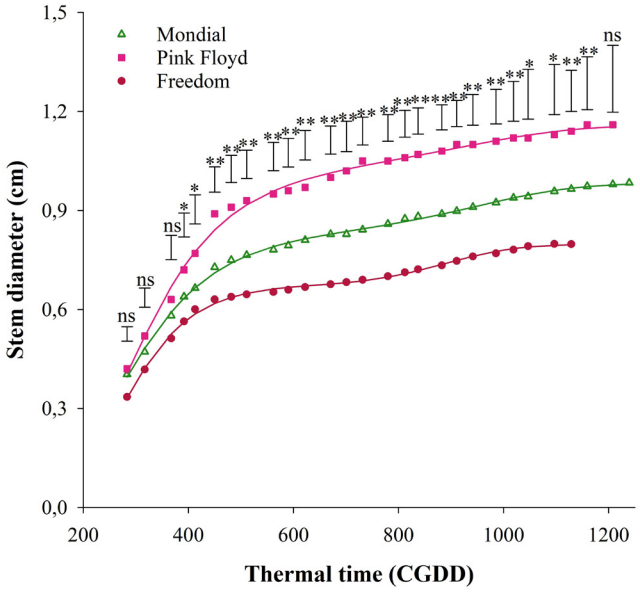
In a phenological study of ten rose varieties, [21] found Freedom to be the earliest, reaching an SL of 73.66 cm at 89 DAC. In contrast, when analyzing five rose varieties, [22] found that the Pink Floyd variety reaches an SL of 91.52 cm at the moment of cutting, while Mondial reaches 90.88 cm, with Pink Floyd being the tallest, surpassed only by the Explorer variety.

[23] mention that the initial phase of growth in a meristem is short and slow, corresponding to the synthesis of growth-promoting substances and a preparatory process before cell division, and that only the subsequent increase in cell volume reflects the effect of their multiplication. According to [24], the sigmoidal growth curve of most plant species includes a linear growth phase, during which cells multiply in preparation for the expansion and elongation phase. The expansion phase occurs due to the softening of the cell walls, followed by the entry of water driven by an osmotic gradient, while elongation involves the expression of genes that synthesize the cell wall components. Similarly, [19] state that, at the end of growth, the rate slows down as the stem ages, which is related to flowering and the filling of the flower button.

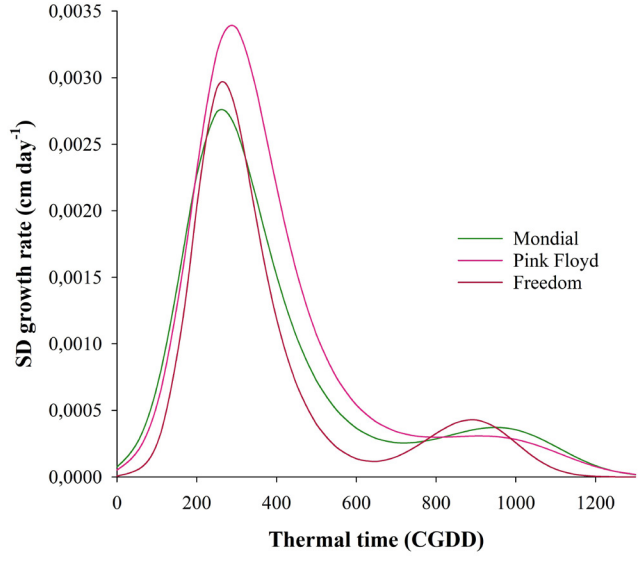
Stem diameter (SD)

Significant differences in SD were observed between treatments from 26 DAC to HPB. The Pink Floyd variety exhibited increased SD (0.72 cm) compared to Mondial and Freedom, starting at 28 DAC (0.638 and 0.563 cm, respectively), and at 75 DAC, when the SD was 1.127, 0.957, and 0.798 cm, respectively. This difference persisted until harvest (Fig. 3a).

The SD of the Mondial variety showed an accelerated initial growth until 33 DAC (450 CGDD). From there, its growth slowed until 51 DAC (731.7 CGDD), just as the stems entered the PB stage. Growth then accelerated again until 70 DAC (1018.8 CGDD), before reaching the CSB stage, which coincided with the flower button's most pronounced growth. Finally, growth stabilized as the plant approached the harvest point at 84 DAC (1239.2 CGDD), with a diameter of 0.983 cm.



(a)



(b)

Figure 3. Fitting the double sigmoid logistic model to a) the growth and b) the growth rate of the stem diameter of roses of the Mondial, Pink Floyd, and Freedom varieties
Note: The vertical bars indicate significant differences according to the Tukey test ($p \leq 0.05$). ns: no differences; * and **: statistical differences at 5 and 1%, respectively.
Source: Authors

Pink Floyd showed a higher SD than the other varieties, with accelerated initial growth until 33 DAC (450 CGDD), corresponding to the highest mitotic activity and the synthesis of the necessary proteins for transitioning from a vegetative to a reproductive stage [25]. Growth then decelerated considerably until 47 DAC (670.5 CGDD), when the stem was in the RB stage. From then until 51 DAC (731.7 CGDD), there was a brief acceleration corresponding to the PB stage. After this phase and up to HPB, growth was constant, and the SD reached 1.16 cm at 82 DAC (1208 CGDD).

The Freedom variety showed an accelerated initial SD growth up to 30 DAC (412.7 CGDD). Growth then decreased until 51 DAC (731.7 CGDD), when the floral stems entered the CB stage. Afterwards, the curve experienced a final acceleration up 65 DAC (941.6 CGDD), followed by stabilization up HPB (77 DAC, 1128.9 CGDD) with a diameter of 0.797 cm.

The increase in SD results from the accumulation of sugars and the formation of the vascular cambium during secondary growth, which supports the developing flower. Therefore, SD is an important parameter since it defines the quality of the floral stem [26]. [22] found significant differences in SD between Pink Floyd and Mondial, with values of 0.98 and 0.92 cm, respectively, which is consistent with our results. Additionally, [27] reported an SD of 0.935 cm at harvest for the 'Freedom' variety.

The SD growth rate fit a double-sigmoid logistic model well for all three varieties, with two maxima (Fig. 3b, Table II). For Mondial, these maxima were 0.00277 and 0.00037 cm GDD^{-1} at 261 and 948 CGDD, respectively. For Pink Floyd, the maxima were 0.00339 and 0.00031 cm GDD^{-1} at 292 and 899 CGDD. Finally, for Freedom, the maxima were 0.00297 and 0.00044 cm GDD^{-1} at 265 and 889 CGDD. This explains why the Pink Floyd variety achieved the highest SD values: it exhibited the highest SD growth rates.

Flower button diameter (FBD)

Significant differences among the three varieties were observed only after 61 DAC, which persisted through subsequent measurements until harvest, with the highest values observed in Freedom (Fig. 4a). Across the three varieties, growth followed a similar curve until 53 DAC (774 CGDD). Afterwards, the curve became less pronounced until 61 DAC (882.5 CGDD). Thereafter, the growth patterns of each variety diverged until harvest, with Freedom showing the greatest FBD growth (4.13 cm), followed by Pink Floyd and Mondial (3.64 and 3.55 cm). These values are higher than the 3.28 cm reported by [19] for Freedom.

For the Mondial variety, the FBD growth conformed to a double sigmoid model, exhibiting two phases of acceleration: the first occurred from 70 to 72 DAC (1018.8 to 1046.7 CGDD), just before the button entered the CSB stage; and the second occurred from 82 DAC (1208 CGDD) until harvest (84 DAC, 1239.2 CGDD).

In the case of Pink Floyd, a slow growth was observed from 45 DAC (639.4 CGDD) to 54 DAC (779.8 CGDD), just before the flower button entered the CB stage. Once it entered this phase (51 DAC; 731.7 CGDD), its growth accelerated noticeably until 72 DAC (1046.7 CGDD), approaching the HPB stage, which occurred at 82 DAC (1208 CGDD).

Table II. Estimates obtained in the growth model for SL, SD, FBD, and FBL by variety

Parameter	Variety	a	b	c	d	e	r^2
SL	Mondial	86.3713	-10.6136	0.032150	-0.000031660	1.2140×10^{-8}	0.9999
	Pink Floyd	85.0504	-12.4500	0.042725	-0.000050117	2.2538×10^{-8}	0.9999
	Freedom	85.0790	-18.2942	0.079808	-0.000118699	6.2992×10^{-8}	0.9999
SD	Mondial	0.98193	-5.92612	0.029069	-0.000039033	1.8809×10^{-8}	0.9999
	Pink Floyd	1.15799	-6.50353	0.030076	-0.000037756	1.7462×10^{-8}	0.9999
	Freedom	0.79700	-8.56798	0.046015	-0.000070345	3.6728×10^{-8}	0.9999
FBD	Mondial	4.65412	-10.1681	0.016681	-0.000008484	1.7523×10^{-9}	0.9987
	Pink Floyd	3.71093	-26.6171	0.082596	-0.000094543	3.9390×10^{-8}	0.9997
	Freedom	5.47054	-2.77091	-0.009346	0.000020640	-8.4103×10^{-9}	0.9991
FBL	Mondial	7.55980	-7.23361	0.009661821	-0.000003246	4.1848×10^{-10}	0.9999
	Pink Floyd	5.47313	2.03354	-0.018353	0.000023124	-6.3646×10^{-9}	0.9998
	Freedom	5.90393	2.79449	-0.026184	0.000037981	-1.3991×10^{-8}	0.9984

Note: SL: stem length; SD: stem diameter; FBD: flower button diameter; FBL: flower button length; a, b, c, d, and e: coefficients of the double sigmoid logistic regression model
Source: Authors

The FBD for Freedom exhibited a slow initial growth from 40 DAC (561.7 CGDD) to 47 DAC (670.5 CGDD). Growth then accelerated, reaching 56 DAC (812.2 CGDD) after the flower button entered the BB stage. From 56 DAC to harvest, growth continued to accelerate until the HPB state was reached (77 DAC, 1128.9 CGDD).

The growth rate of the FBD was best fit by a simple sigmoid logistic model for all three varieties, each showing a single maximum (Fig. 4a). For Mondial, the rate was 0.00583 cm GDD^{-1} at 944 CGDD, corresponding to the period between BB and CSB. For Pink Floyd, the rate was 0.00922 cm GDD^{-1} at 995 CGDD, occurring at the beginning of the CSB stage (997.52 CGDD). For Freedom, the rate was 0.0096 cm GDD^{-1} at 946 CGDD, after the CSB stage, indicating that Freedom reaches the largest FBD size with the highest growth rate. Additionally, it can be inferred that Pink Floyd requires more CGDD to achieve an adequate FBD.

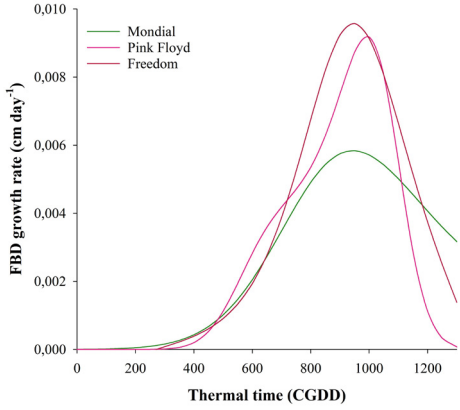
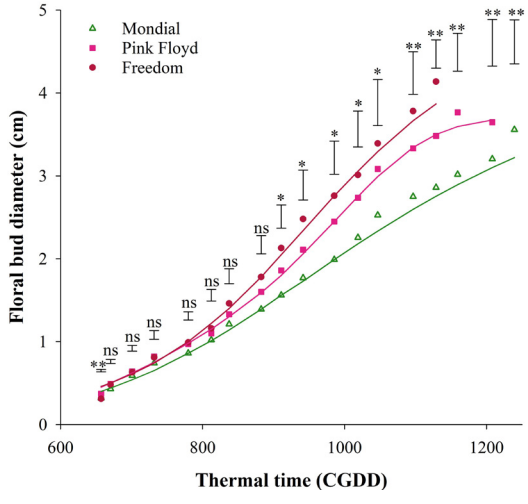
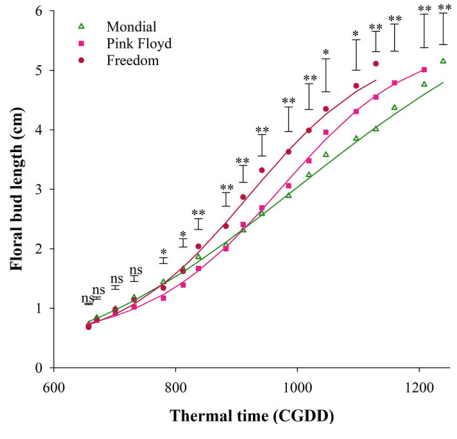


Figure 4. Fitting the double sigmoid logistic model to a) the growth and b) the growth rate of the floral button diameter of roses of the Mondial, Pink Floyd, and Freedom varieties
Note: The vertical bars indicate significant differences according to the Tukey test ($p \leq 0.05$). ns: no differences; * and **: statistical differences at 5 and 1%, respectively.
Source: Authors





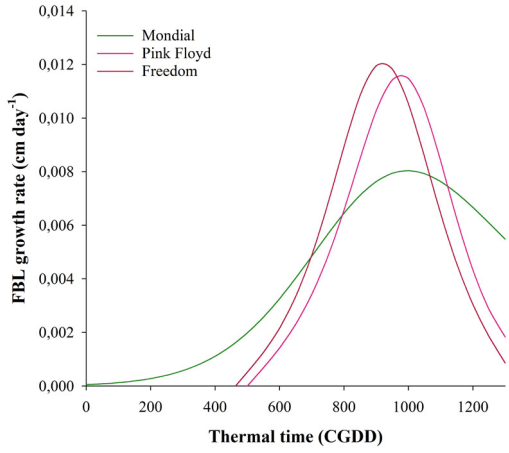


Figure 5. Fitting the double sigmoid logistic model to a) the growth and b) the growth rate of the floral button length (FBL) of roses of the Mondial, Pink Floyd, and Freedom varieties
Note: The vertical bars indicate significant differences according to the Tukey test ($p \leq 0.05$). ns: no differences; * and **: statistical differences at 5 and 1%, respectively.
Source: Authors

Flower button length (*FBL*)

This parameter showed significant differences from 49 DAC until harvest, with the Freedom variety reporting the highest values (5.40 cm) at harvest, followed by Mondial and Pink Floyd with 5.14 and 5.00 cm (Fig. 5a). These results confirm that the flower button growth of Freedom was the most robust among the studied varieties. This marked acceleration in FBD growth across the three varieties can be attributed to the expansion of the flower button, a process regulated by auxins, which are responsible for cell expansion in stems and flowers and are influenced by factors such as temperature [23]. According to [28], the optimal temperature range for cut roses is 27 °C. Higher temperatures accelerate the growth of thin stems with smaller, poorly developed flower buttons, whereas temperatures below 4 °C inhibit shoot growth. The temperatures recorded in this study exhibited thermal fluctuations that could affect stem development (Fig. 1).

However, these values are lower than those reported by [29], who found FBLs of 5.93 and 6.38 cm for Freedom and Mondial, respectively, while [22] reported 5.97 and 5.42 cm for Pink Floyd and Mondial, respectively. [30] note that flower button size is influenced by factors such as temperature, humidity, solar radiation, and nutrition, with the latter having significant implications for quality. In Colombia, the soil is often saturated with high levels of phosphorus and boron before flowering, leading to toxicity and reducing the number and size of buttons per m^2. This excess could have been at work in this study, affecting flower button size and resulting in lower FBL values. FBL is an essential parameter for flower producers worldwide, as a quality stem should be thick, long, and vertical, with large flower buttons, bright colors, and a long vase life [22].

The growth dynamics of FBL in the Mondial variety are less pronounced, but a growth trend was identified from 46 DAC (657.1 CGDD) to 51 DAC (731.7 CGDD), just before the stem enters the PB stage. Growth then accelerated to 68 DAC (985.6 CGDD), coinciding with the start of the CSB stage. After this peak, a slight deceleration occurred, and growth continued until the HPB stage was reached at 84 DAC (1239.2 CGDD).

The growth rate of the FBL followed a single maximum for all three varieties, suggesting a simple sigmoid logistic model (Fig. 5a). The Mondial variety showed a maximum growth rate of 0.00802 cm GDD^{-1} at 1001 CGDD, corresponding to the phenological phase between BB and CSB. Pink Floyd exhibited the highest FBL growth rate of 0.0116 cm GDD^{-1} at 979 CGDD, just before the start of the CSB stage (997.52 CGDD). For Freedom, the growth rate was 0.0121 cm GDD^{-1} at 918 CGDD, at the beginning of the CSB stage, indicating that this variety has the highest FBL values, which are similar to its FBD results. Conversely, Mondial requires more CGDD but does not show larger flower buttons, suggesting that it may be a variety with smaller flowers or one that needs more nutrition for optimal floral development.

The FBL of Pink Floyd best fits a double-sigmoid logistic growth model (Table II). The initial growth was slow from 39 to 51 DAC, after which it accelerated. This acceleration occurred as the stems entered the PB stage, and it peaked between the BB stage (884.43 CGDD) and the beginning of the CSB stage (997.52 CGDD). Growth then stabilized until the HPB stage was reached at 82 DAC (1208 CGDD).

Conclusions

The Mondial, Pink Floyd, and Freedom varieties required different accumulations of GDD to reach each phenological stage, and they exhibited varying levels of total chlorophyll as measured by our SPAD units. The earliest variety to reach flowering was Freedom, which accumulated 1134 GDD, while the latest one was Mondial, with 1233 GDD—it also recorded the lowest average values for stem and flower length and diameter. The flower buttons of the Freedom variety had the highest values for FBD and FBL, indicating the most robust stem and flower buttons. The flower button diameter and length showed a single peak in growth rate across all the evaluated varieties, suggesting a fit to a simple sigmoid logistic model. SD growth was best described by a double-sigmoid logistic model across all three varieties, and SL followed a simple sigmoid logistic model for Mondial and Pink Floyd. In contrast, Freedom was best described by a double-sigmoid logistic growth model, suggesting that this variety may require more frequent management during cultivation. This study presents growth models that predict the phenological stages of three rose varieties, aimed at optimizing work scheduling and harvest planning to improve production efficiency and decision-making in commercial systems.

CRediT author statement

J. A. H.: conceptualization, methodology, formal analysis, and supervision; M. J. G.: formal analysis, writing (review and editing); M. J. R.: conceptualization, data collection, workflow, writing (original draft), background research.

Conflicts of interest

The authors declare no conflicts of interest.

Access to research data

The datasets generated and/or analyzed during this study are available from the authors upon reasonable request

Statement on artificial intelligent

The authors did not use IAG. The authors take full responsibility for the contents of this publication

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