

Growth, phenology, and yield of six pea (*Pisum sativum* L.) varieties under plastic cover conditions in the Andean region of Boyacá

Crecimiento, fenología y rendimiento de seis variedades de arveja (*Pisum sativum* L.) cultivadas bajo cubierta plástica en la región andina de Boyacá

Yair Castañeda Caro ^{1,3}, Oscar Humberto Alvarado Sanabria ^{2,4}, Diego Alejandro Gutiérrez Villamil ^{2,5},
Javier Giovanni Álvarez Herrera ^{1,6}, Marilcen Jaime Guerrero ^{1,7}.

¹Universidad Pedagógica y Tecnológica de Colombia. Tunja, Colombia. ²Universidad Nacional de Colombia, sede Bogotá. Bogotá, Colombia.

³ ✉ yair.castaneda@uptc.edu.co; ⁴ ✉ ohalvarados@unal.edu.co; ⁵ ✉ digutierrezvi@unal.edu.co;

⁶ ✉ javier.alvarez@uptc.edu.co; ⁷ ✉ marilcen.jaime@uptc.edu.co



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Abstract

Pea (*Pisum sativum* L.) is a crop of outstanding global importance due to its high protein content. In Colombia, the department of Boyacá has lost its leading position in pea production due to the lack of development of new varieties better adapted to local environmental conditions. This limitation has restricted the yield potential of peas and led to a decline in the productivity of cultivated areas. On that basis, the phenological development, biomass production, and seed yield of six pea varieties grown under plastic cover in the city of Tunja, Boyacá, were evaluated. A completely randomized design was implemented with six treatments and five replications. The treatments consisted of six introduced pea varieties: Alejandrita, Síe, Afila, Rizada, Santa Isabel, and San Isidro. The variety Rizada required 208 accumulated growing degree days (CGDD) to reach 50 % emergence, whereas Alejandrita, Síe, and Afila needed 177 CGDD, indicating variability in their initial thermal requirements. When the plants accumulated 330 CGDD, the Síe, Afila, Santa Isabel, and San Isidro varieties had already formed the first node, while Alejandrita and Rizada required more thermal time to reach this stage. Flowering began at 1092 CGDD for all varieties, except Santa Isabel, which required 1208 CGDD, and was classified as a late-maturing variety. All varieties reached physiological maturity at 1805 CGDD and full harvest maturity at 2075 CGDD. The variety Santa Isabel exhibited the highest biomass production, while the bush-type varieties (Síe and Alejandrita) developed more basal branches. The variety Síe produced the lowest 100-seed weight. Lastly, Santa Isabel showed the highest green seed yield, significantly outperforming Síe and Alejandrita, which had the lowest.

Keywords: Biomass, leaflets, reproductive nodes, thermal time, vegetative nodes.

Resumen

La arveja (*Pisum sativum* L.) es un cultivo de gran importancia a nivel mundial debido a su alto contenido proteico. En Colombia, el departamento de Boyacá ha perdido protagonismo en su producción, en gran parte debido a la falta de desarrollo e introducción de nuevas variedades adaptadas a las condiciones ambientales locales. Esta limitación ha restringido el potencial de rendimiento del cultivo, lo que genera una disminución en la productividad de las áreas cultivadas. Por ello, en el presente estudio se evaluaron el desarrollo fenológico, la producción de biomasa y el rendimiento de semillas de seis variedades de arveja cultivadas bajo condiciones de cubierta plástica en Tunja, Boyacá. Se utilizó un diseño completamente aleatorizado con seis tratamientos y cinco repeticiones. Las variedades introducidas fueron Alejandrita, Síe, Afila, Rizada, Santa Isabel y San Isidro. La variedad Rizada requirió 208 grados día de crecimiento acumulados (GDDA) para alcanzar el 50 % de emergencia, mientras que Alejandrita, Síe y Afila necesitaron solo 177 GDDA, evidenciando variabilidad en la respuesta térmica inicial. Al alcanzar los 330 GDDA, Síe, Afila, Santa Isabel y San Isidro ya habían formado su primer nodo, mientras que Alejandrita y Rizada requirieron mayor acumulación térmica. La floración se inició a los 1092 GDDA en todas las variedades, excepto Santa Isabel, que lo hizo a los 1208 GDDA, clasificándose como variedad de maduración tardía. Todas las variedades alcanzaron la madurez fisiológica a los 1805 GDDA y madurez para la cosecha a los 2075 GDDA. Santa Isabel presentó la mayor producción de biomasa, mientras que las variedades de tipo arbustivo (Alejandrita y Síe) desarrollaron más ramas basales. La variedad Síe tuvo el menor peso de 100 semillas. Finalmente, Santa Isabel obtuvo el mayor rendimiento de semillas verdes, superando significativamente a Síe y Alejandrita, que registraron los valores más bajos.

Palabras clave: biomasa, folíolos, nodos reproductivos, nodos vegetativos, tiempo térmico.

Introduction

Pea is a crop of outstanding global importance due to its use as fresh and dry grains, which are rich in protein, vitamins, phosphorus, iron, magnesium, and fiber (Wu *et al.*, 2023). Additionally, they contain flavonoids and carotenoids, essential antioxidants that help reduce the risk of developing various diseases (Fatima *et al.*, 2024). Globally, legume production increased by 34 % in 2023, while in Europe, it reached 44 %, primarily due to production growth associated with higher crop yields achieved over the past decade (Uskutoğlu and İdikut, 2023). In 2019, China, India, and France were the world's leading pea-producing countries, with outputs of 13.3, 5.5, and 2.8 million tons (t), respectively (Lambrecht *et al.*, 2023). In Colombia, pea production reached 80 477 t across 29 749 hectares in 2021, with the departments of Nariño, Cundinamarca, and Boyacá as the main producers (Agronet, 2023).

Global warming has been associated with increases in the average global temperature, with projections indicating an increase of up to 2 °C by 2100 (Malhi *et al.*, 2021). Consequently, negative effects on pea productivity are expected. Such climatic alterations reduce seed yield and quality, and also affect photosynthetic performance and plant phenology (Sadras *et al.*, 2019). In Colombia, pea production in Boyacá has declined considerably over the past 15 years, dropping from 10 363 t in 2008 to 5147 t in 2013 and 5661 t in 2021. In contrast, the department of Nariño has experienced an increase in yields (Agronet, 2023), highlighting a disparity in agronomic development. Pea germplasm has been developed in Nariño since 2007; in contrast, in Boyacá, the limited introduction of new varieties adapted to local conditions has hindered crop development, leading to reduced productivity in cultivated areas across the department (Checa-Coral *et al.*, 2021).

In pea plants, the genotype-environment interaction determines the duration of vegetative and reproductive periods (Lambrecht *et al.*, 2023), which is crucial for efficient variety selection. A deep understanding of this interaction facilitates the identification of areas with optimal agroclimatic conditions for cultivation and enables the proper implementation of specific genotypes (Achenef *et al.*, 2024). In this context, evaluating new genetic material in specific regions is a valuable strategy for adapting to climate change, as it offers alternatives to enhance the productive potential of peas under adverse conditions (Töpfer and Trapp, 2022). Likewise, identifying phenological stages based on thermal time in pea varieties with morphological differences in canopy development helps predict crop cycle duration, estimate harvest dates, and optimize product marketing, ultimately strengthening crop productivity (Lambrecht *et al.*, 2023).

In this sense, pea varieties with the *afila* gene are expected to exhibit different behavior compared to traditional varieties. Therefore, the objective of this research was to evaluate the phenological development and yield of six pea varieties under the environmental conditions of Tunja, using a plastic cover.

Materials and methods

Location

The research was conducted in the experimental greenhouse at La María farm, part of the Grupo de Investigaciones Agrícolas (GIA) affiliated with the Universidad Pedagógica y Tecnológica de Colombia (UPTC). The study site is located in the municipality of Tunja, Boyacá, at 5°33'10" N latitude, 73°21'36" W longitude, and an altitude of 2691 m. The greenhouse has a chapel-type structure with overhead ventilation and consists of four buildings, each measuring 30 m in length and 6 m in width, covered with 7-gauge plastic. Figure 1 shows the temperature and relative humidity recorded inside the greenhouse throughout the crop cycle, from February 24, 2023 (sowing) to June 25, 2023 (harvest), using an RHT20 data logger (Extech Instruments, NH, USA). During the experiment, the average maximum, mean, and minimum temperature values were 30.9 ± 4.5 °C, 17.1 ± 1.4 °C, and 9.7 ± 1.9 °C, respectively. The average relative humidity was $70.2 \% \pm 4.4 \% (\pm \text{standard deviation})$.

Plant material

Pea seeds from six varieties were used: two of short climbing types (< 1 m tall) (Alejandrita and Síe), and four climbing types (Afila, Rizada, Santa Isabel, and San Isidro). The Santa Isabel and San Isidro varieties were acquired commercially from LERL Seeds (Distribuciones Semillas LERL Ltda., Colombia) and Fenalce (Federación Nacional de Cultivadores de Cereales, Leguminosas y Soya, Colombia), respectively. The Genetic Resources Unit of the Universidad Nacional de Colombia, Bogotá campus, donated the Alejandrita and Síe seeds. Similarly, the Afila and Rizada seeds were provided by the seed bank of the GRICAND research group at the Universidad de Nariño (Table 1). These latter varieties are characterized by the *afila* gene, which causes the leaflets to transform into tendrils. All seeds were disinfected with the fungicide Vitavax® (Adama Agricultural Solutions, Israel) to ensure safe seed emergence and seedling development.

Experimental design

A completely randomized design was implemented with six treatments, each corresponding to a different pea variety (Alejandrita, Síe, Afila, Rizada, Santa Isabel, and San Isidro). Each treatment included five

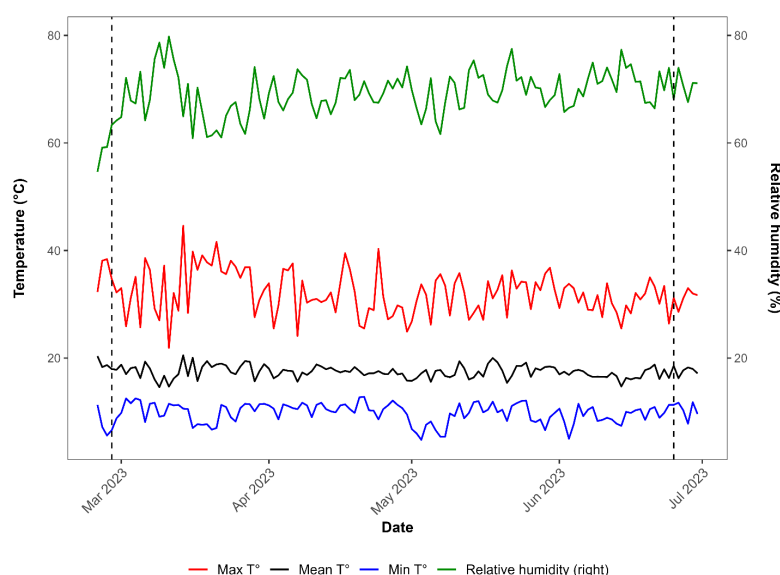


Figure 1. Temperature and relative humidity values recorded in the La María greenhouse (UPTC) during the experimental period. The dotted lines indicate the beginning (February 27, 2023) and end (June 25, 2023) of the experiment.

Table 1. Morphological and phenological traits of the six pea (*Pisum sativum* L.) varieties evaluated in this study

Variety	Leaf type	Growth habit	Average height (cm)	Flowering time (days)	Time to first harvest (days)	100-green seed weight (g)	Reference
Alejandrita	Leafy	Bush type	65	57	97	60.3	Ligarreto (2017a)
Sie	Leafy	Bush type	70	61	95	56.5	Ligarreto (2017b)
Afila	Leafless (afila)	Climbing	187	-	117	68	Checa-Coral et al. (2021)
Rizada	Leafless (afila)	Climbing	171	-	117	71.03	Checa-Coral et al. (2021)
Santa Isabel	Leafy	Climbing	170	64	120	65	Galindo and Clavijo (2009)
San Isidro	Leafy	Climbing	185	59	112	41	Checa-Coral et al. (2021)

replicates, resulting in a total of 30 experimental units, each with an area of 4.5 m². The crop was directly sown into clay-textured soil. The spatial arrangement consisted of 15 cm between plants and 1 m between rows. Two seeds were sown at each planting site, resulting in 60 plants per experimental unit and a total of 1800 plants across the 30 units. Each row was equipped with an irrigation line, containing a 4 L h⁻¹ dripper per planting site. Irrigation was applied for 30 minutes daily across all treatments. Throughout the experiment, soil volumetric water content was maintained above 35 %, monitored regularly using a TDR 150 (Spectrum Technologies Inc., Aurora, IL, USA) to ensure consistent moisture conditions.

As part of the cultivation practices, the first fertilization was carried out 50 days after sowing (DAS), applying 11 g m⁻² of diammonium phosphate (DAP, [(NH₄)₂HPO₄]), 15 g m⁻² of urea (CH₄N₂O), and 8 g m⁻² of potassium chloride (KCl). A second fertilization was performed at 85 DAS, using 31 g m⁻² of calcium nitrate (Ca(NO₃)₂), 11 g m⁻² of urea, and 8 g m⁻² of KCl. In both applications, the fertilizers were physically mixed and incorporated on the right side of each row, below seed level.

Additionally, two phytosanitary applications were carried out to prevent powdery mildew (*Podosphaera pannosa*) at 66 and 76 DAS. The fungicide Azuco® (Colinagro SA, Colombia), containing colloidal sulfur as the active ingredient, was applied at a dose of 50 cm³ per 20 L of water using a backpack sprayer.

Response variables

The mean emergence time (MET) of the seedlings was recorded, defined as the number of days until each plant developed two fully expanded leaves. The MET was calculated using Equation 1, when 50 % of the seeds had emerged, following the methodology suggested by Galindo and Clavijo (2009). Seedlings were counted every three days.

$$MET = \frac{\sum \text{Emergence time of each seedling}}{\text{Total number of seedlings}} \quad (\text{Eq. 1})$$

Similarly, the cumulative growing degree days (CGDD) were determined using Equation 2, where T_{average} represents the average daily temperature, and T_{base} is the base temperature (0 °C) (Miller et al., 2001).

$$CGDD = \sum_{i=1}^n T_{average} - T_{base} \quad (\text{Eq. 2})$$

The number of vegetative nodes (VN) was counted once the leaves, tendrils, and stipules were fully expanded. Likewise, the number of reproductive nodes (RN) was recorded from the main stem of each plant when the flower petals were fully expanded. The onset of flowering was defined as the moment when 50 % of the observed plants had at least one floral bud (Galindo and Clavijo, 2009). At the end of the experiment, the total number of reproductive nodes of all branches of each plant was estimated.

Equatorial pod diameter (EPD) was measured after pollination and monitored until the pod reached physiological maturity, using a digital caliper (Mitutoyo Corporation, Japan) with a precision of 0.05 mm.

Total biomass production: At harvest, dry biomass production was assessed for different plant organs (stem, stipules, leaflets, empty pods, and seeds) using a VİBRA AJ220E digital scale (Shinko Denshi Co., Ltd., Japan), after drying samples at 60 °C for 72 h in a UNB500 oven (Memmert GmbH + Co. KG, Germany).

Leaf area: The stipule leaf area (SLA) was determined through photographic analysis, with the images processed using ImageJ software (Figure 2), following the methodology described by Easlon and Bloom (2014).

Leaflet area (LA) was estimated using allometric models proposed by Galindo (2006) for pea crops. This involved measuring petiole length and the number of leaflet pairs to estimate leaflet length and determine total leaf area. The total plant leaf area was calculated by summing the SA and LA for each experimental unit.

Yield components and harvest index: Additionally, the yield components of peas were evaluated, as suggested by Chandra and Polisetty (1998), including the number of basal branches and the number of pods, seeds, and green seed yield per basal branch. The fresh weight of 100 green seeds was also determined. Furthermore, the harvest index (HI) was calculated using Equation (3).

$$HI(\%) = \frac{\text{Dry mass of seeds}}{\text{Total dry mass}} \quad (\text{Eq. 3})$$

Statistical analysis

Before performing the analysis of variance for treatments and canopy types, tests for normality and homogeneity of variances were performed on the collected data. Subsequently, a Tukey's test ($p < 0.05$) was performed to compare the treatment means. In addition, a Pearson correlation analysis was conducted using data from all variables. The

statistical analysis was conducted using SAS v.9.2e software (SAS Institute Inc., Cary, NC, USA). The graphs were designed in SigmaPlot software version 14.0.0.124 (San José, CA: Systat Software, Inc.).

Results and discussion

Seedling emergence

Significant differences in MET and CGDD for emergence were observed among the evaluated varieties (Figure 3). The Rizada variety exhibited the longest mean seedling emergence time, with values of 11 DAS and 207.6 CGDD, followed by Santa Isabel and San Isidro, which had values of 9.58 DAS (186.5 CGDD) and 9.42 DAS (183.8 CGDD), respectively. The varieties with the shortest MET were Alejandrita, Síe, and Afila, with an average of 8.75 DAS and 176.69 CGDD, which was lower than the previously reported values for Santa Isabel (11 to 14 DAS (171.44 - 198.93 CGDD) under greenhouse conditions and 32 DAS (316.55 CGDD) in open-field conditions) (Galindo and Clavijo, 2009). The greenhouse microclimate played a key role in reducing MET, since the average temperature (Figure 1) tends to increase by 5 °C to 10 °C in greenhouse environments (Omid and Shafaei, 2005).

Seedling emergence is influenced by temperature increases, which accelerate enzymatic and metabolic processes (Gong *et al.*, 2022). This phenomenon favored seedling emergence across all varieties (Figure 3) due to the higher temperatures inside the greenhouse. According to Benti and Petros (2017), MET in peas is a critical factor for genotype and variety selection, as shorter emergence times are associated with a shorter biological cycle. Early-emerging genotypes are characterized by an emergence time of 6 to 8 DAS (Benti and Petros, 2017), which aligns with the behavior of Alejandrita, Síe, and Afila varieties under greenhouse conditions.

In terms of emergence percentage (Figure 3B), Afila and Síe displayed significantly higher emergence than Santa Isabel, which showed the lowest values. Alejandrita, Rizada, and San Isidro presented intermediate levels with no significant differences among them. Beyond thermal conditions, emergence dynamics are also affected by seed morphological traits such as size and seed coat thickness. In peas, thinner and smoother seed coats enhance water permeability, accelerating imbibition and radicle protrusion (Williams *et al.*, 2024). This may partly explain the superior emergence performance observed in Afila and Síe. Conversely, the lower emergence percentage of Santa Isabel may be attributed to a thicker or less permeable seed coat that delays water uptake and germination.

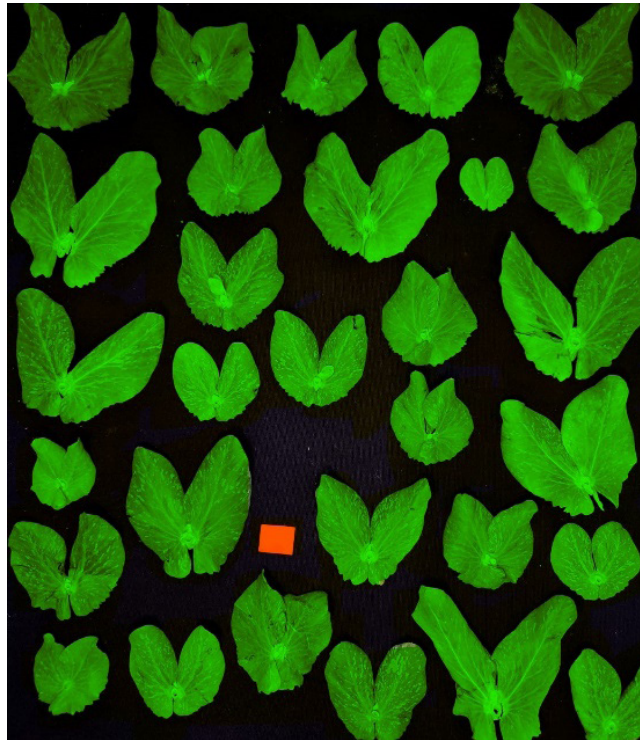


Figure 2. Image of *P. sativum* stipules processed using the ImageJ software to estimate leaf area.

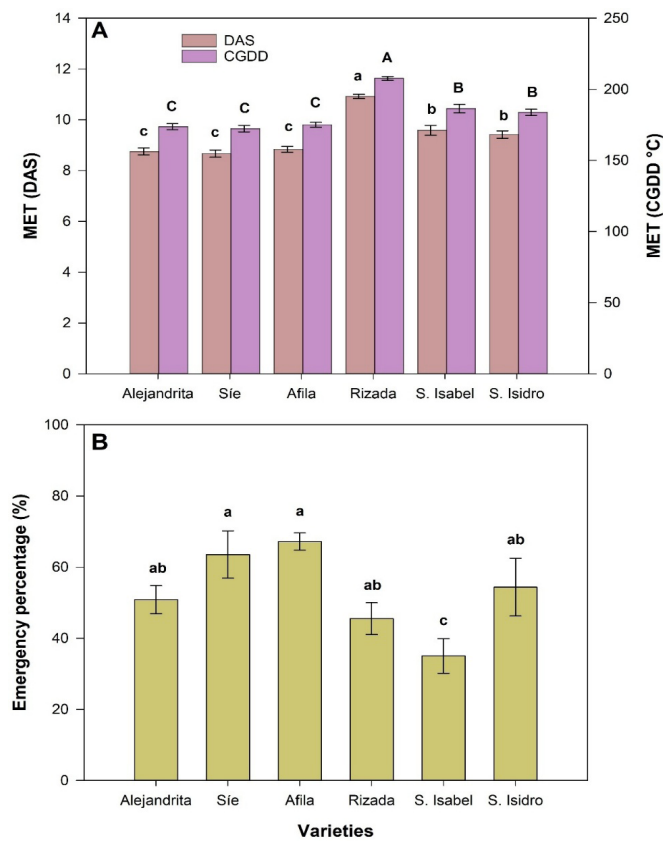


Figure 3. Mean emergence time (MET) in days after sowing (DAS) and cumulative growing degree days (CGDD) (**A**), and emergence percentage (**B**) of six pea (*Pisum sativum* L.) varieties grown under greenhouse conditions. *Lowercase and uppercase letters in columns of the same color indicate significant differences between treatments ($p < 0.05$). The bars represent the standard error ($n = 10$).

Vegetative nodes (VN) and reproductive nodes (RN)

The development of VN and RN on the main stem showed significant differences over time and tended to increase as CGDD accumulated (Figure 4). VN production began at 329.83 CGDD (18 DAS), where the Rizada variety exhibited the highest node production, while Alejandrita and Síe had not yet completed node development. Between 705.65 and 1174.40 CGDD (39 and 66 DAS, respectively), the Afila, Rizada, and Santa Isabel varieties showed the highest node production, with values of 16.25, 16.24, and 17.58 VN at 1174.40 CGDD, respectively. In contrast, Síe, Alejandrita, and San Isidro exhibited lower VN production, with 15.25, 12.66, and 13.66 VN, respectively.

These results indicate that the varieties carrying the *afila* gene (Afila and Rizada) produce more VN, along with Santa Isabel, Colombia's most widely cultivated variety (Villani and Demason, 1999). According to Villani and Demason (1999), varieties with the recessive *afila* gene can produce up to 27 nodes. The absence of leaflets, due to the homozygous recessive condition of the *afila* gene, likely promotes increased node production to generate more stipules, thereby meeting the photosynthetic demand required for growth and grain filling. Additionally, Alejandrita and Síe exhibit a short growth habit, but show greater vegetative development compared to the other varieties.

The emergence of the first RN on the main stem began at 1091.6 CGDD (61 DAS) (Figure 4, blue line) for all varieties except Santa Isabel. Significant differences were observed between treatments from

1091.6 CGDD to 1702.1 CGDD (61 and 96 DAS), with Afila, Rizada, and San Isidro showing the highest RN production, with values of 11.42, 11.43, and 11.58, respectively. In contrast, Santa Isabel, Alejandrita, and Síe produced fewer RN, with values of 10, 9.33, and 9.17 at 1702.17 CGDD, respectively.

The onset of RN formation occurred when the plants accumulated 1091.64 CGDD (for Alejandrita, Síe, Afila, Rizada, and San Isidro) and 1207.61 CGDD (68 DAS) (for Santa Isabel), marking the beginning of the reproductive and flowering stage. By 1702.17 CGDD (96 DAS), RN development had ceased in all varieties. In contrast, Olivier and Annandale (1998) reported that different pea varieties reached flowering between 770.8 and 890.8 CGDD under open-field conditions, estimating that flowering initiation (at least one open flower in 50 % or more of the plants) occurred between 724 and 835 CGDD.

For the varieties Alejandrita, Síe, Afila, Rizada, and San Isidro, the first RN appeared after the development of 12.33, 14.25, 15.83, 15.75, and 13.42 VN, respectively, at 1057.56 CGDD (59 DAS) (Figure 4). In Santa Isabel, the first RN emerged after 17.58 VN, which developed at 1174.40 CGDD (66 DAS), aligning with findings by Pacheco *et al.* (2010) for pea genotypes cultivated in Colombia, where the first flowering node appeared between 12.8 and 19.0 VN.

The total number of VN in *P. sativum* is influenced by both environmental and genotypic variability, as the species exhibits an indeterminate growth habit (Munier-Jolain *et al.*, 2010). Consequently, the total number of RN varies by genotype. However, the onset of RN formation is a phenotypic trait with relatively low genetic variability, though it can be influenced by photoperiod and temperature, depending on

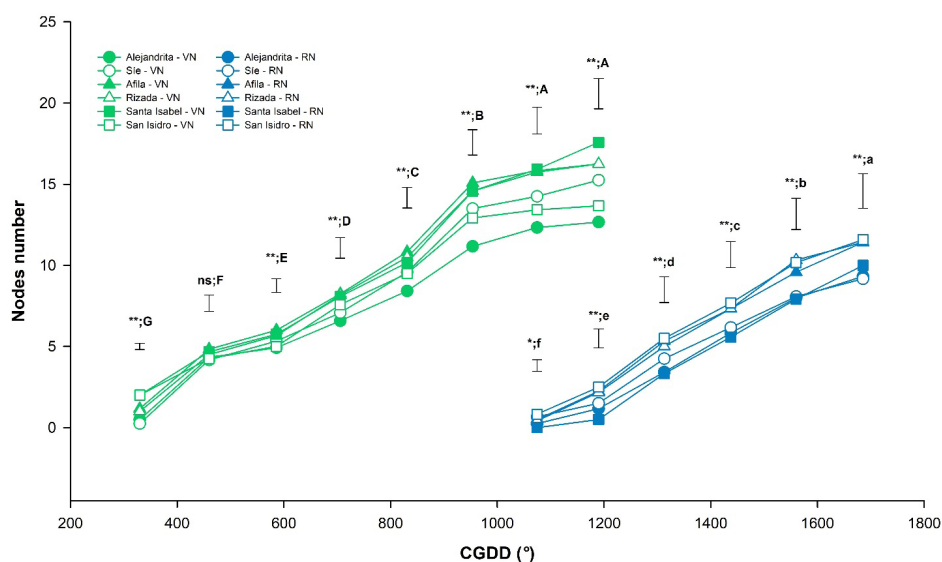


Figure 4. Appearance of vegetative nodes (VN) (green lines) and reproductive nodes (RN) (blue lines) in six peas (*Pisum sativum* L.) varieties under greenhouse conditions. ns: not significant; * and ** indicate statistically significant differences between treatments ($p < 0.05$ and $p < 0.01$, respectively). Characters before and after the semicolon indicate significant differences between treatments and over time, respectively, according to Tukey's test ($p < 0.05$) for vegetative and reproductive nodes. The bars represent the standard error for all treatments ($n = 10$).

the genotype (Williams *et al.*, 2022). For the Santa Isabel variety grown under greenhouse conditions, reports indicate that the first RN appears at node 20, classifying it as a late-flowering variety (Galindo and Clavijo, 2009), consistent with the results of this study.

Equatorial pod diameter (EPD)

No significant differences in EPD were observed among the evaluated varieties (Figure 5). Pod growth began at 1312.86 CGDD (74 DAS), with an initial average diameter of 1.97 mm, progressively increasing until physiological maturity at 1805.03 CGDD (102 DAS, 714 CGDD after flowering) to a final diameter of 13.5 mm. These results are similar to those of Pekşen *et al.* (2004), who reported an average pod thickness (EPD) of 12.10 mm across 15 pea genotypes.

According to Munier-Jolain *et al.* (2010), EPD is a reliable indicator for identifying the onset of seed filling after flower pollination, as well as the completion of physiological maturity. Similarly, Ney *et al.* (1993) found that pea pods reach physiological maturity—in terms of cell number, length, and dry mass—at 600 CGDD after flowering.

Biomass production

In all varieties, harvest was carried out at 118 DAS and 2075.03 CGDD, which aligns with findings by Lambrecht *et al.* (2023), who reported an average thermal time of 2000 CGDD from sowing to harvest maturity for the pea variety Itapuã 600 Isla[®], grown in five different seasons.

The Santa Isabel variety exhibited significantly higher dry mass production of stipules, leaflets, and pods and, consequently, greater biomass per branch compared to the other varieties, reaching values of 19.95 g, 32.10 g, 32.21 g, and 150.88 g, respectively (Figure 6). In this regard, Checa-Coral *et al.* (2021) stated that this variety is the most widely cultivated in Colombia due to its desirable commercial traits, such as large grains and pods, as well as its indeterminate (volute) growth habit, which contributes to greater pod biomass (Figure 6). Additionally, Santa Isabel was characterized by having the highest number of vegetative nodes among the evaluated varieties (Figure 4), enabling it to accumulate more leaflets and stipule biomass (Figure 6) under greenhouse conditions.

The Alejandrita and Sie varieties exhibited the lowest stem dry mass, with values of 17.97 g and 18.09 g, respectively, while the remaining varieties had an average of 29.46 g (Figure 6). Similarly, these two varieties accumulated less dry biomass from stipules and leaves, leading to a lower total dry mass per branch. This could be attributed to their short growth habit, which differs from the tall climbing growth type observed in the other varieties. As a result, they tend to develop fewer vegetative nodes and shorter stems (UNAL, 2023).

The Rizada and Afila varieties, which carry the *afila* gene, showed significant differences in stipule dry biomass accumulation, with lower values than Santa Isabel and San Isidro, but higher than Alejandrita and Sie. According to Checa-Coral *et al.* (2021), *afila* varieties replace leaflets with tendrils, which could partially explain the significant increase in stem

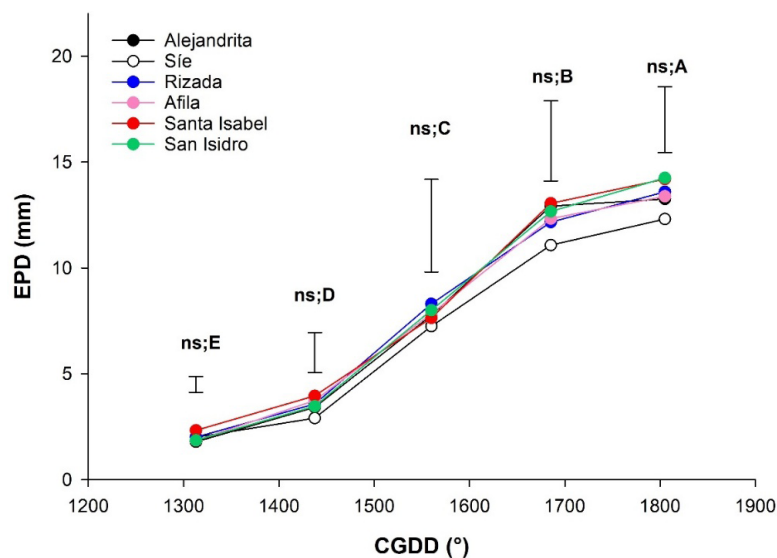


Figure 5. Pod growth of six pea (*Pisum sativum* L.) varieties as a function of cumulative growing degree days (CGDD) under greenhouse conditions. EPD: equatorial pod diameter; ns: not significant ($p < 0.05$) between treatments. Characters before and after the semicolon indicate significant differences between treatments and over time, respectively, according to Tukey's test ($p < 0.05$). The bars represent the standard error for all treatments ($n = 10$).

dry mass compared to other varieties. Additionally, Rizada and Afila exhibited good vegetative and reproductive node development; however, this did not result in increased stipule or pod biomass.

Santa Isabel and San Isidro produced the highest pod dry biomass (33.4 g and 23.8 g, respectively), whereas the remaining varieties averaged 21.2 g. Conversely, seed dry mass did not show significant differences among varieties, with an overall mean of 34.9 g. This suggests that, although Santa Isabel had heavier pods, likely due to its higher number of reproductive nodes and phenotypic characteristics, the seeds reached similar final masses to those of the other varieties. Munier-Jolain *et al.* (2010) stated that variation in seed mass among pea varieties is primarily determined by differences in seed cell number, a trait associated with genotype. Therefore, these genotypes are unlikely to exhibit significant differences in this phenotypic trait.

Leaf area

Significant differences were found in leaflet area (LA), stipule area (SA), and total leaf area (TLA) across varieties (Figure 7). Santa Isabel had the highest leaf area values for both stipules and leaflets, also reflected in TLA, highlighting the strong vegetative development of this variety. Similarly, the leafless varieties (Afila and Rizada) exhibited high LAS values compared to Sie, Alejandrita, and San Isidro. Except for Santa Isabel, no significant differences in TLA were observed among the remaining varieties.

The greater leaf area values observed in Santa Isabel can be attributed to its higher number of nodes, which allowed for increased leaflets and stipule production under greenhouse conditions (Figure 4). Likewise, the *afila*-gene varieties exhibited high SA values, which compensated for the absence of leaflets, resulting in no significant differences in TLA compared to the other varieties. This suggests that these varieties compensate for the absence of leaflets by developing larger stipules and a greater number of nodes, thereby maintaining an adequate photosynthetic capacity (Giovanardi *et al.*, 2018).

In this regard, Pantoja *et al.* (2014) noted that pea plants carrying the *afila* gene are more resistant to lodging due to their greater tendril production, have a lower incidence of leaflet diseases, and are more efficient in water use, as they experience reduced transpiration losses due to their smaller leaf surface area. These characteristics make *afila* varieties more drought-tolerant.

Yield components

Table 2 shows that there were significant differences between treatments regarding the number of basal branches (NBB), with plants of the Alejandrita variety producing the highest NBB, followed by Sie and Santa Isabel. In this regard, Munier-Jolain *et al.* (2010) state that the appearance of primary branches on the main axis is a phenotypic trait that varies under specific conditions. They affirm that the number of branches depends on total plant growth and its interaction with the environment, as it is susceptible to water and nutrient deficiencies and high planting densities.

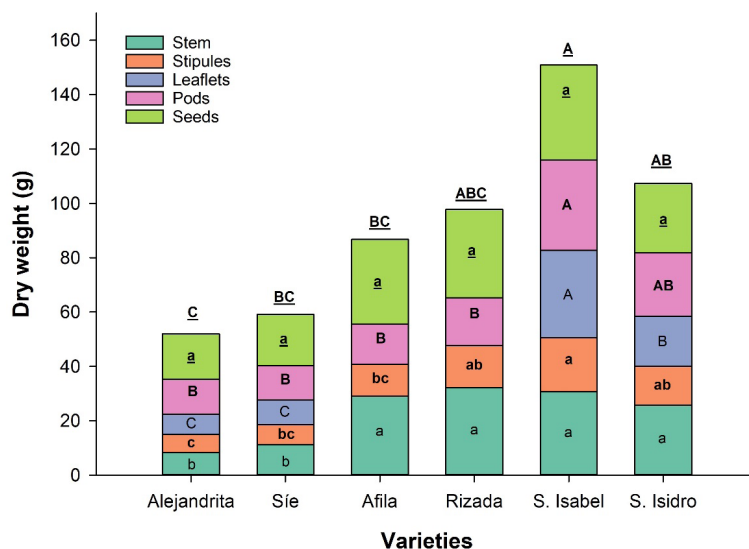


Figure 6. Dry biomass production per basal branch of (A) stem, (B) stipules, (C) leaflets, (D) pods (without seeds), (E) seeds, and (F) total biomass of six peas (*Pisum sativum* L.) varieties under greenhouse conditions. Different letters between columns and boxes indicate significant differences between treatments and between varieties, respectively, according to Tukey's test ($p < 0.05$). ns: not significant according to ANOVA ($p < 0.05$). The bars represent the standard error ($n = 10$).

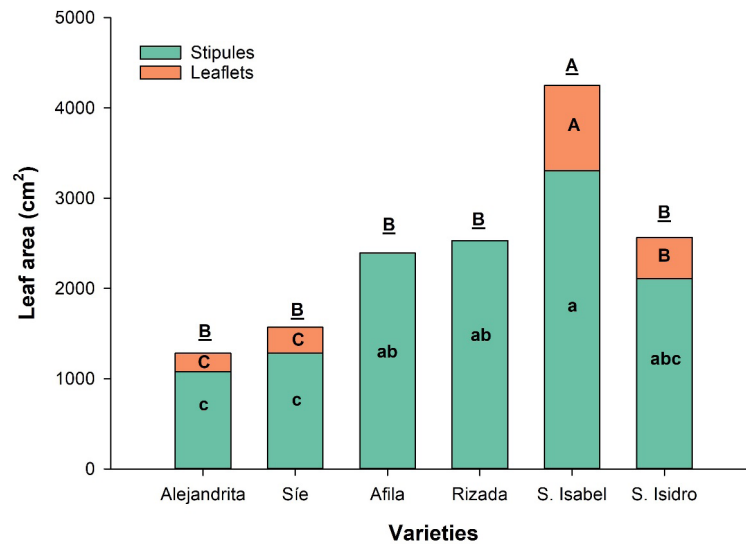


Figure 7. Leaf area production per basal branch of (A) leaflets and stipules, and (B) total leaf area, of six pea (*Pisum sativum* L.) varieties under greenhouse conditions. Lowercase, uppercase, and underlined uppercase letters indicate significant differences between leaflet area (LA), stipule area (SA), and total leaf area (TLA), respectively, according to Tukey's test ($p < 0.05$). The bars represent the standard error ($n = 10$).

There were no significant differences between varieties for the number of pods per branch (NPB) and the number of seeds per branch (NSB), which had average values of 26.83, 39.5, and 208.53, respectively. Although not statistically significant, the high reproductive node production and biomass accumulation in Santa Isabel resulted in 36 % more NPB than the average of the other varieties. However, the low harvest index (HI) (Table 2) suggests a greater allocation of resources to vegetative rather than reproductive growth. Galindo and Clavijo (2009) attribute this to the fact that Santa Isabel grown in a greenhouse produces fewer pods per branch than in open-field conditions. In this sense, pea plants exposed to high temperatures may exhibit reduced yield, as elevated temperatures can shorten the time to flowering, decrease pod number, and reduce seed size (Jiang *et al.*, 2020). Although the plants in this study were not subjected to heat stress, temperature may still have affected the yield of the Santa Isabel variety.

The Afila and Rizada varieties showed yield component values similar to the other varieties, except for Santa Isabel (Table 2). However, Mihailović (2008) reports that *afila* varieties are more productive than non-*afila* varieties. Despite the high HI values observed for Afila and Rizada in this study, their yields did not exceed those of the other varieties.

The Sie variety, which exhibits a determinate growth habit, showed a significantly reduced 100-seed weight (100SW), suggesting low seed filling during development, despite its dry biomass production. This reduction is likely due to the genotypic characteristics of the variety. Conversely, UNAL (2023) reports that Alejandrita and Sie typically produce 35 and 33 pods per branch, respectively,

which is substantially higher than the average of 21 pods per branch recorded for these varieties in this study (Table 2). However, the Rizada variety achieved 27 NPB, comparable to the 28 NPB reported by Checa-Coral *et al.* (2021).

Green seed yield (GSY) per basal branch did not show statistically significant differences among the six pea varieties ($p > 0.05$), although numerical variation was evident. Santa Isabel recorded the highest average GSY, while Sie and Alejandrita presented the lowest values. Although no significant differences were detected, the trends observed suggest that genotypic differences may influence GSY potential. The higher GSY in Santa Isabel could be linked to its high pod and seed production per branch, suggesting efficient reproductive growth despite a low HI.

Analysis by canopy type

When grouped by canopy type, bush-type-leaved varieties (Alejandrita and Sie) showed the highest NBB and moderate GSY (Table 3). However, they recorded the lowest TLA and dry biomass accumulation (STDW, PDW, SDW). The climbing-leaffless group (Afila and Rizada) had the lowest NBB but higher NPB and NSB, with intermediate GSY. Their TLA and TDW surpassed the bush types, as did biomass in stem, stipules, and seed. Finally, the climbing-leaved varieties (Santa Isabel and San Isidro) combined moderate NBB with the highest NPB, NSB, GSY, and TLA. They also accumulated the highest total dry biomass. The harvest index (HI) was the highest in climbing-leaffless varieties and the lowest in climbing-leaved ones.

Table 2. Yield components of six pea (*Pisum sativum* L.) varieties under greenhouse conditions

Variety	NBB	NPB ^{ns}	NSB ^{ns}	GSY ^{ns} (g branch ⁻¹)	100SW (g)	HI
Alejandrita	2.4a ± 0.3	31.1 ± 5	183.8 ± 27	71.8 ± 12.8	70.8a ± 2	31.62ab ± 2.5
Síe	1.7ab ± 0.3	34.8 ± 5	185.7 ± 30	64.2 ± 15	58.4b ± 1	28.97ab ± 3.1
Afila	1.2b ± 0.1	36.3 ± 5	171.5 ± 21	89.6 ± 13.3	68.2a ± 2	35.08a ± 1.4
Rizada	1.2b ± 0.1	41.7 ± 6	219.6 ± 37	103.3 ± 23.8	71.7a ± 2	31.63ab ± 3.0
Santa Isabel	1.7ab ± 0.2	49.10 ± 8.8	260.20 ± 41.5	126.3 ± 18.4	73.55a ± 1.8	22.47b ± 2.0
San Isidro	1.1b ± 0.1	35.35 ± 4.0	194.20 ± 21.7	86.7 ± 10	68.93a ± 2.4	24.79ab ± 2.0

*ns: no significant; NBB: number of basal branches; RNB: reproductive nodes per branch; NPB: number of pods per branch; NSB: number of seeds per branch; 100SW: 100-seed weight; GSY: green seed yield; HI: harvest index. Different lowercase letters within rows indicate significant differences among treatments ($p < 0.05$). ± represents the standard error ($n = 10$).

Table 3. Morphological, phenological, and yield-related traits of six pea (*Pisum sativum* L.) varieties with different canopy types under greenhouse conditions

Parameter	Varieties					
	Alejandrita	Síe	Afila	Rizada	Santa Isabel	San Isidro
	Bush type-leafy	Climbing-leafless	Climbing-leafy			
NBB	2.05 a		1.20 b		1.35 b	
NPB	32.98 a		39.0 a		46.52 a	
NSB	184.74 a		195.5 a		245.35 a	
GSY	67.97 a		96.43 a		106.5 a	
100SW	64.59 b		69.94 a		71.23 a	
HI	30.29 a		33.36 a		23.63 b	
MET (CGDD)	172.09 b		190.91 a		185.1 a	
EMG (%)	57.17 a		56.33 a		44.67 a	
VN	13.9 b		16.25 a		15.7 a	
RN	9.4 b		11.45 a		10.95 a	
TLA	1425.47 c		2461.85 b		3405.74 a	
LA	245.32 b		0 c		699.27 a	
SA	1180.16 b		2461.85 a		2706.47 a	
TDW	55.51 c		92.27 b		129.13 a	
SDW	17.77 b		31.91 a		30.27 ab	
PDW	12.69 b		16.21 b		28.26 a	
LDW	8.31 b		0 c		25.25 a	
STIDW	6.95 b		13.49 a		17.13 a	
STDW	9.78 d		30.65 a		28.20 a	

*ns: no significant. Different lowercase letters within rows indicate significant differences among treatments ($p < 0.05$). ± represents the standard error ($n = 10$). NBB: number of basal branches; RNB: reproductive nodes per branch; NPB: number of pods per branch; NSB: number of seeds per branch; 100SW: 100-seed weight; GSY: green seed yield; HI: harvest index; NBB: number of basal branches; RN: reproductive nodes per branch; VN: vegetative node per branch; NPB: number of pods per branch; NSB: number of seeds per branch; 100SW: 100-green seed weight; HI: harvest index; EMG%: emergency percentage; MET: mean time to emergence; GSY: green seed yield per branch; SA: stipule area; LA: leaflet area; TLA: total leaf area; STDW: stem dry weight; LDW: leaflet dry weight per branch; STIDW: stipule dry weight; PDW: pod dry weight; SDW: seed dry weight; TLA: total dry weight.

The bush-type leafy growth strategy promotes early branching but limits leaf development and biomass accumulation per branch, resulting in reduced seed yield per unit. This suggests that increasing the number of branches does not necessarily enhance productivity in dense planting systems. In contrast, climbing-leafless varieties showed a favorable partitioning of photoassimilates, characterized by fewer branches, higher leaf area, and more efficient biomass use. Their higher HI values reflect superior conversion of vegetative biomass into seeds, making them ideal for efficient canopy systems. On the other hand, climbing-leafy types demonstrated the highest potential in terms of absolute seed yield per branch, supported by their extensive canopy and greater biomass accumulation in all organs. However, their lower HI indicates that a larger proportion of biomass is retained in vegetative tissues. These results provide insight into varietal selection strategies: bush types for branching potential, leafless types for efficient assimilate partitioning, and leafy climbing types for maximizing per-branch productivity under low-density or trellised systems.

Correlation analysis

Based on the Pearson correlation coefficient (Figure 8), significant associations were found between GSY and various morphological traits measured per basal branch in six pea varieties. Yield showed strong positive correlations with SDW, LDW, STDW, STIDW, and PDW, suggesting that greater biomass accumulation in individual organs contributes directly to productivity. Additionally, TLA, NSB, and NPB were strongly correlated with yield, highlighting their relevance in achieving high productivity. These relationships indicate that well-developed vegetative traits promote and reflect reproductive efficiency and seed production per branch.

Conclusions

Pea varieties differed notably in their adaptability to thermal conditions, growth habits, and yield potential under plastic-covered greenhouse conditions in

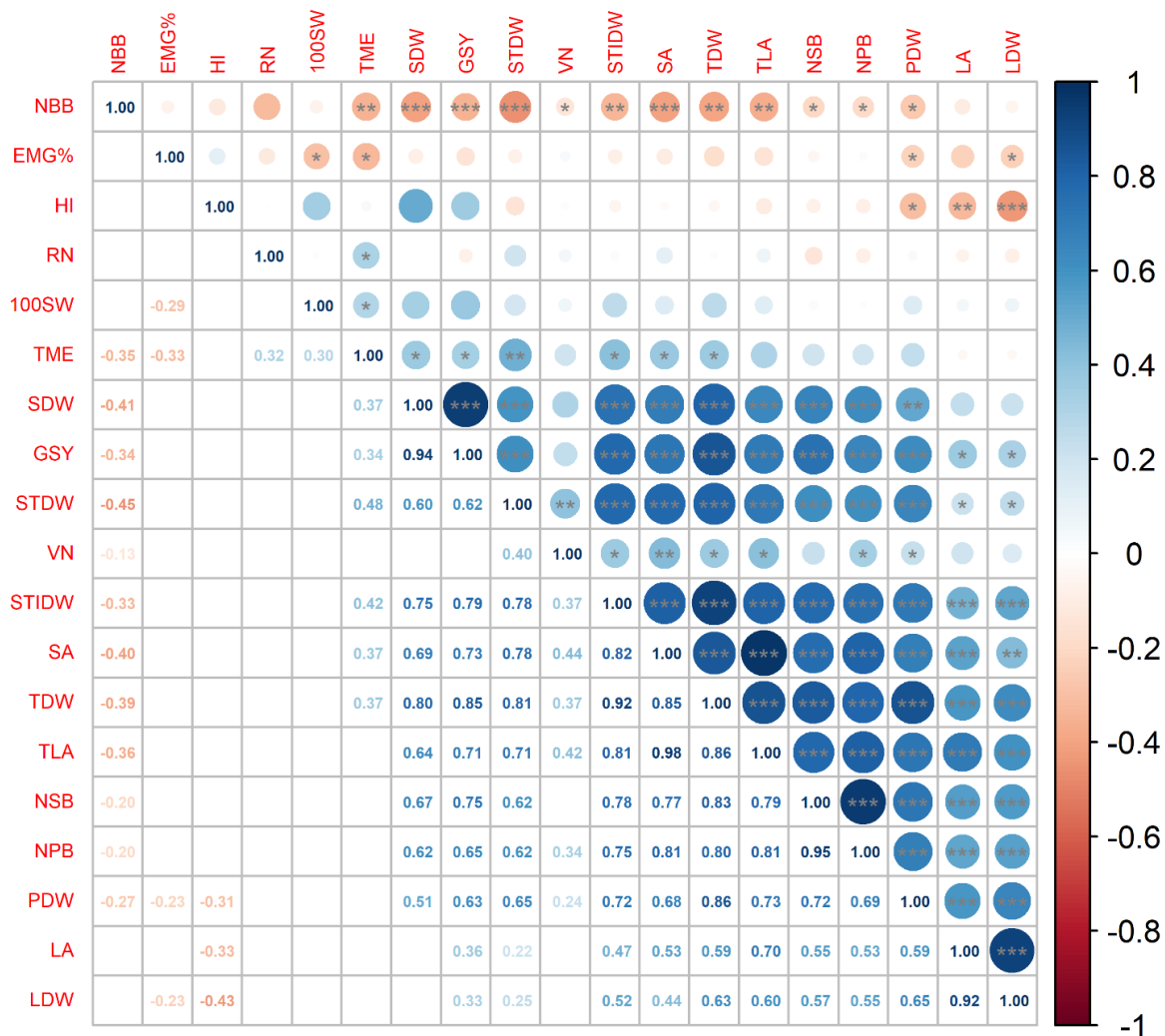


Figure 8. Pearson correlation matrix among morphological and yield-related traits in six pea (*Pisum sativum* L.) varieties. Circle size and color represent the strength and direction of the correlation coefficients. Asterisks indicate significance levels (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). NBB: number of basal branches; RN: reproductive nodes per branch; VN: vegetative nodes per branch; NPB: number of pods per branch; NSB: number of seeds per branch; 100SW: 100-green seed weight; HI: harvest index; EMG%: emergency percentage; MET: mean time to emergence; YIELD: seed yield per branch; SA: stipule area; LA: leaflet area; TLA: total leaf area; STDW: stem dry weight; LDW: leaflet dry weight per branch; STIDW: stipule dry weight; PDW: pod dry weight; SDW: seed dry weight; TLA: total dry weight.

Boyacá. Varieties such as Afila and Síe established more rapidly due to their earlier seedling emergence and lower thermal requirements, while Rizada and Santa Isabel required more growing degree days to emerge. Although most varieties synchronized at later developmental stages, Santa Isabel stood out as a late-flowering genotype that produced the highest biomass and green seed yield. In contrast, Síe and Alejandrita, despite developing more basal branches, showed limited seed development and lower 100-seed weight.

When varieties were grouped by canopy type, clear physiological patterns emerged. Bush-type leafed varieties promoted early branching but limited leaf expansion and assimilate production, leading to lower biomass and yield per branch. Climbing-leafless types, such as Afila and Rizada, showed better source-sink balance, converting biomass more

efficiently into seed, as reflected by their higher HI. Meanwhile, climbing-leafed types, like Santa Isabel, combined a large canopy and the highest reproductive output, although a greater portion of biomass was retained in vegetative tissues. These differences suggest that bushy genotypes may be suitable where branching is desired, leafless climbing types excel in partitioning efficiency and canopy management, and leafy climbing varieties offer maximum productivity per branch in low-density or trellised systems. Furthermore, correlation analysis supported these patterns by revealing strong positive associations between vegetative traits, such as leaf area and biomass, with reproductive traits like seed number and yield. This indicates that canopy structure and biomass accumulation directly influence productivity when biomass partitioning is efficient. Altogether, these findings suggest that selection strategies in

pea should consider canopy architecture, thermal response, and source-sink efficiency to optimize yield potential in high-altitude systems like those in Boyacá.

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