Yield and development of winter and spring rapeseed (*Brassica napus* L.) at different sowing dates in temperate environments

Desarrollo y rendimiento de colza (*Brassica napus* L.) invernal y primaveral ante distintas fechas de siembra en ambientes templados

Miguel Pereyra Iraola, Mateo Zubiri, José Luis Bodega, María Luján Nagore,
Gastón Darwich, Roberto Dionisio Martínez *

Originales: *Recepción:* 04/06/2024- *Aceptación:* 18/10/2024

Abstract

Optimal sowing dates should match the crop-critical period with favorable conditions. In rapeseed, growth stages change among spring and winter cultivars. This study characterized changes in rapeseed phenology with varying sowing dates to determine critical periods in both winter and spring cultivars. The trial took place in Balcarce, Argentina, where a winter-type variety and a spring-type were sown on eight different dates in a randomized complete block design with three replicates. Phenology was monitored weekly, and yield was evaluated at the end of the season. Changes in sowing dates and cultivars led to variations in the timing of critical periods. Considering the experimental conditions, the optimal sowing window was between April and July for sowing either rapeseed cultivar. However, the winter variety did not bloom for sowing dates after July, while the spring variety showed yield reductions due to frosts for sowing dates before the end of April. Changes in sowing date resulted in differences in timing and duration of vegetative and reproductive stages, generally leading to shorter crop cycles. However, in late sowing, winter cultivars lengthened their life cycle to the point of not reaching flowering during the growing season.

Keywords
autumn sowing date • winter sowing date • vernalization • frost

Universidad Nacional de Mar del Plata. Facultad de Ciencias Agrarias. Ruta 226. km 73.5. Balcarce. C. P. 7620. Argentina. * rmartinez@mdp.edu.ar

Resumen

La fecha óptima de siembra debe hacer coincidir el período crítico del cultivo con condiciones favorables. Existen diferencias en la ubicación de las etapas de desarrollo de colza entre las variedades primaverales e invernales. El presente estudio se realizó para caracterizar los cambios en la fenología de la colza al variar la fecha de siembra para determinar el momento del período crítico en ambas variedades invernales y primaverales. El ensayo se llevó a cabo en Balcarce, Argentina, donde se sembraron una variedad tipo invernal y otra de tipo primaveral en ocho fechas diferentes. Se utilizó un diseño de bloques completos al azar con tres repeticiones y se monitoreó la fenología semanalmente, además de evaluar el rendimiento de cada tratamiento al final del ciclo. El período crítico se desplazó a diferentes períodos dependiendo de la fecha de siembra y la variedad. Bajo las condiciones experimentales, hubo una ventana ambiental óptima entre abril y julio para sembrar, tanto la variedad primaveral como la invernal. Sin embargo, la variedad invernal no floreció en siembras posteriores a julio, y la variedad primaveral experimentó reducciones en el rendimiento debido a las heladas en siembras antes del fin de abril. Las variedades ante las diferentes fechas de siembra presentaron diferencias tanto en la ubicación como en la duración de las etapas vegetativas y reproductivas, tendiendo a acortar su ciclo. Sin embargo, en las siembras más tardías, la variedad invernal alargó su ciclo hasta el punto de no alcanzar la floración durante la temporada de crecimiento.

Palabras clave

fecha de siembra otoñal • fecha de siembra invernal • vernalización • heladas

Introduction

Brassica napus L., commonly known as rapeseed or canola (particularly the "double-zero" variety with low erucic acid and glucosinolates), holds substantial economic value, primarily attributed to its edible oil and significance in bioenergy (18). Over the last decade, rapeseed has been cultivated on approximately 35 million hectares globally (38), with key production regions in the European Union, Asia, and North America (35). Effective optimization of rapeseed crop productivity depends on selecting the sowing date and cultivar type. Rapeseed cultivars are categorized into winter and spring varieties (37). Winter cultivars require vernalization and are sown in the autumn, with their development rate being temperature-dependent within specific ranges (5, 10, 21, 32). Winter cultivars are mainly cultivated in areas that meet the required temperature thresholds, particularly in Northern Europe, the United States, and China. In contrast to winter cultivars, spring cultivars do not require vernalization and are sown at later dates (16). Primary production areas for spring cultivars include Canada, with minor cultivation areas in India and South America at earlier sowing dates (17). Nevertheless, no significant differences in productivity have been reported between winter and spring cultivars in environments that fulfill their specific requirements (31). However, a wider period of sowing dates could modify cultivar relative performance.

Rapeseed development has various growth stages, from leaf rosette formation to seed maturation. Commonly used phenological scales for the study of rapeseed growth and development are Silvester-Bradley and Makepeace (1984) and Arnoud (1989). Temperature plays a primary role in determining the duration of growing stages (12, 34), although rapeseed exhibits a long-day photoperiodic response (26). The number of leaves is contingent on the length of the vegetative phase, although immature pods can also perform photosynthetic functions (28). Plants can develop multiple floral branches, which form pods containing oil-rich seeds (19). The optimal sowing date is one where the crop critical period matches with the most favorable environmental conditions. This critical period starts with the onset of flowering, lasting approximately four weeks, and is a crucial phase during which pod numbers per plant and flower abortion levels are determined (22). Additionally, crop physiological status during the first half of seed filling is a key factor (27). Regardless of the cycle duration and available water supply, which can affect the productivity of any crop, rapeseed, in particular, exhibits a high sensitivity to elevated temperatures during the flowering period (24, 29). Furthermore, the crop remains vulnerable to frost events even during the seed-filling stage (31). Late sowings are not recommended because as temperature increases during seed filling, seed oil content decreases (13, 36).

In temperate environments, grain yield can reach 4000 kg ha^{-1} under optimal conditions (10, 15). Where winters are mild, it is feasible to use either early-sown spring genotypes or winter varieties (11, 16). Nevertheless, inappropriate sowing dates could potentially shorten the crop cycle for both types of cultivars (7). The success of the rapeseed crop depends on choosing a suitable sowing date to avoid delays in flowering and suboptimal environmental conditions during seed filling. In temperate regions, winter varieties should have autumn sowing dates, and spring varieties should have winter sowing dates. However, meteorological and operational factors could delay the sowing date and compromise the optimal conditions for crop growth. Therefore, there is a need to evaluate how different sowing dates could modify the phenology and stages of the rapeseed crop using both spring and winter cultivars across a wide range of dates. Moreover, it is crucial to analyze how the management of the sowing date optimizes crop yield depending on the type of cultivar. This study aimed to characterize changes in rapeseed phenology by varying sowing dates to determine the timing of critical periods and yield in both winter and spring cultivars.

Materials and methods

The experiment was conducted during the 2015/2016 growing season at the Experimental Research Station in Balcarce, Province of Buenos Aires, Argentina (37°45' S-58°18' W) 130 meters above sea level. Two rapeseed cultivars were sown: a winter type (Vectra, from QualityCrops) and a spring type (Bioaureo 2386, from Nuseeds), using an experimental seeder under conventional tillage. Sowing was conducted at a high density to establish the initial plant stand, and thinning was performed after crop emergence to achieve the target density (70 pl/m^2). Experimental design consisted of randomized complete blocks with three replicates, conducted in parallel strips across eight different sowing dates, corresponding to different days of year (DOY): April 23, 2015 (F1: DOY 113), May 13, 2015 (F2: DOY 141), June 1, 2015 (F3: DOY 152), June 24, 2015 (F4: DOY 175), July 10, 2015 (F5: DOY 191), August 5, 2015 (F6: DOY 217), August 27, 2015 (F7: DOY 239), and September 14, 2015 (F8: DOY 257). Each experimental unit had seven furrows 5 m long with 0.21 m distance between furrows, with the total surface area of each experimental unit being 7.35 m^2.

Throughout the crop development, phenology was closely monitored twice a week, with a specific focus on the rosette stages with 4 (B4) to 6 (B6) developed leaves, the onset of stem elongation (D1), flowering (F1), and physiological maturity (MF), following the European phenological classification INRA-CETIOM (4). Each growth stage was considered to start when 50% of the plants showed their specific characteristics. Thermal sum calculations were calculated using a base temperature of 0°C (21). Meteorological data, including air temperature, incident radiation, precipitation, and potential evapotranspiration, were obtained from a meteorological station located approximately 500 meters from the experimental site. To estimate the water deficit throughout the crop growing season, a water balance was conducted using potential evapotranspiration (ETP) calculated through the Penman-Monteith method (2).

The trial was monitored weekly to ensure disease and weed control. In addition to phenology tracking, the yield of each treatment was determined. At the end of the growing season, harvesting was conducted by collecting 1-meter from each of the three central rows within the plots. Harvested seeds were then processed using a stationary thresher, and their weight was recorded to calculate the hectare yield based on the harvested area.

All the variables were analyzed using the statistical software INFOSTAT (8). An analysis of variance was performed, and the Fisher Least Significant Difference (LSD) test for mean comparison was used, with a significance level of $P < 0.05$.

Results and discussion

Environmental conditions

Rainfall was comparatively low during June, September, and December. However, there was a soil profile recharge in August. The water balance analyzed the relationship between rainfall and potential evapotranspiration (figure 1). Mild water deficits were consequently recorded in May, with moderate deficits in September and November, and severe deficits persisting in December. Water deficits may affect flowering and later grain filling under some sowing dates.

Blue columns represent accumulated monthly rainfall, orange columns denote atmospheric demand as potential evapotranspiration (ETP), and light blue columns illustrate the resulting balance from their difference.

Las precipitaciones acumuladas al mes en columnas azules, la demanda atmosférica en forma de evapotranspiración potencial (ETP) en columnas naranjas y el saldo resultante de su diferencia en columnas celestes.

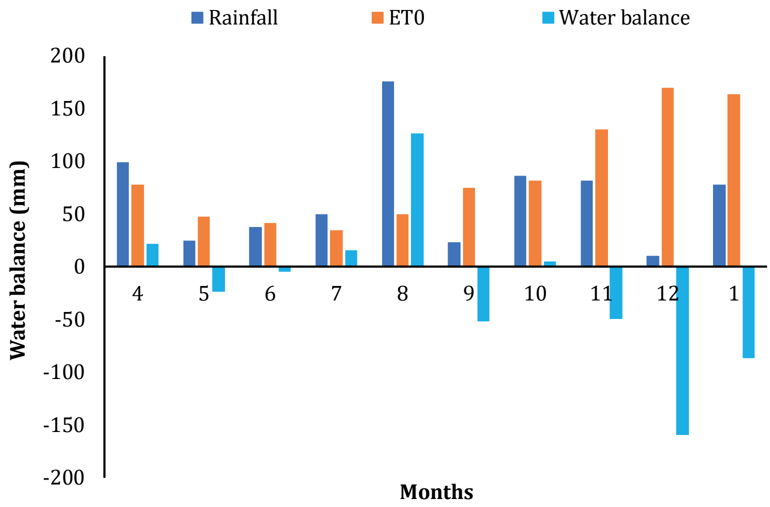


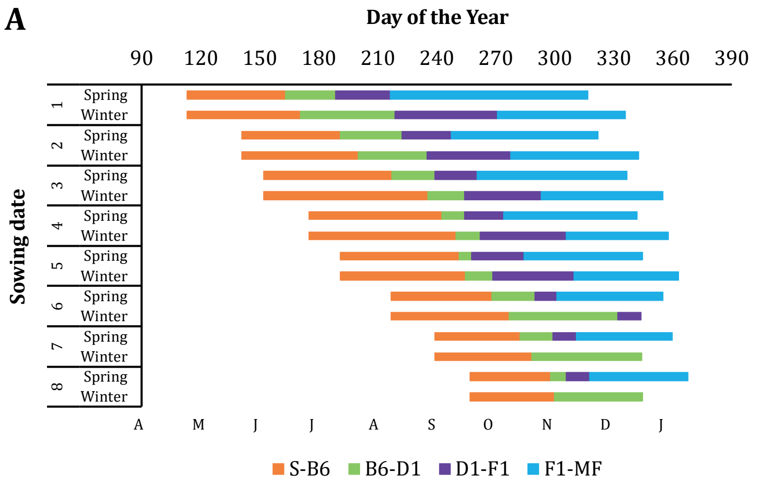
Figure 1. Water balance during the 2015-16 season for Balcarce, in the Buenos Aires province, Argentina.

Figura 1. Balance hídrico durante la temporada 2015-16 para Balcarce, provincia de Buenos Aires, Argentina.

Crop development

As the sowing date was delayed, the average length of the crop cycles became shorter (figure 2A, page XXX). The winter cultivar generally exhibited a longer cycle than the spring cultivar, but after the sixth sowing date, the winter cultivar did not complete its cycle. Critical growth periods occurred at different times when changing the sowing date and between the cultivars. These results align with previous studies from the 2008/2009 season in Paraná, where the cultivars exhibited different responses due to the delayed sowing dates (7).

From the fifth sowing date onward, the growth cycle of the winter cultivar changed from shortening to extending because the vernalization requirements were not satisfied. Vernalization-requiring cultivars increase their development rate as temperature accumulates from 4°C to 9°C. From the 250th day of the year (coinciding with the emergence of the winter cultivar sown on the sixth sowing date), a noticeable decrease in the number of days with minimum temperatures below 7 and 9°C was observed (figure 2B, page XXX). Consequently, the winter variety sown after July did not flower by the time of harvest of the other treatments.



2B Number of days per decade with minimum temperatures below 3 (blue), 7 (light blue), and 9°C (red) and photothermal quotient (dashed green) for the year 2015.

2B Número de días por década con temperaturas mínimas inferiores a 3 (azul), 7 (azul claro) y 9°C (rojo) y cociente fototérmico (verde discontinuo) para el año 2015.

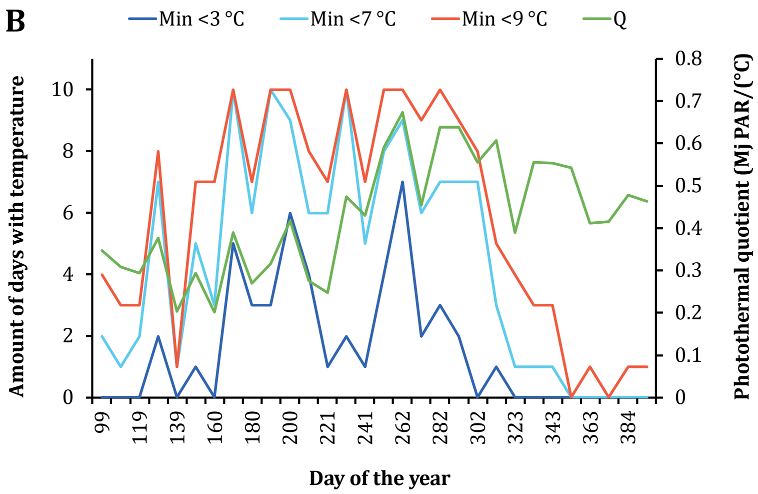
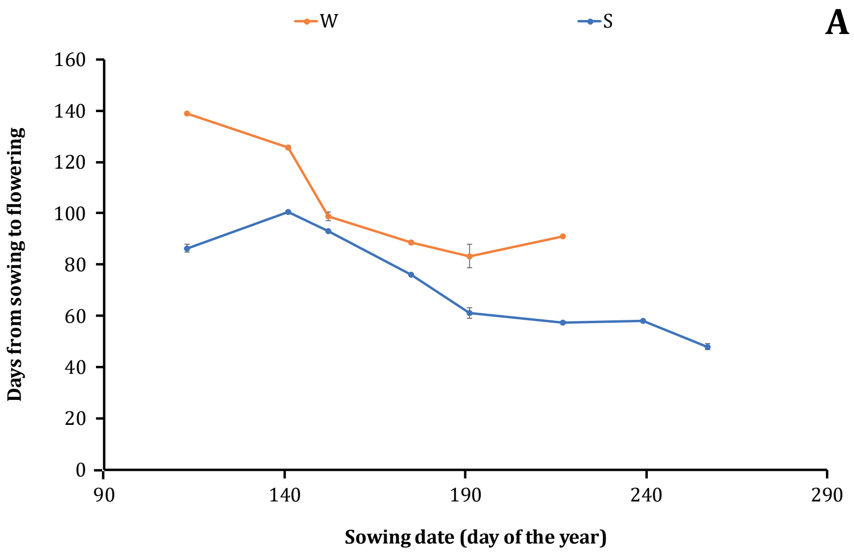


Figure 2A. Duration of the stages Sowing-6 leaves (S-B6 in red), 6 leaves-to inflorescence period (B6-D1 in green), appearance of inflorescence-beginning of flowering (D1-F1 in purple) and flowering - physiological maturity (F1-MF in light blue) expressed in days of the year for two cultivars analyzed and eight sowing dates evaluated.

Figura 2A. Duración de las etapas Siembra - 6 hojas (S-B6 en rojo), 6 hojas - aparición de la inflorescencia (B6-D1 en verde), aparición de la inflorescencia - inicio de floración (D1-F1 en morado) y floración - madurez fisiológica (F1-MF en celeste) expresado en días del año para los dos cultivares analizados y las ocho fechas de siembra evaluadas.

The duration from emergence to flowering period expressed in days presented a significant interaction between the sowing date and cultivar type ($p \leq 0.0001$). For the spring cultivar, the vegetative period was reduced for seven of the eight sowing dates because of delayed sowing (figure 3A, page XXX). The winter cultivar also tended to shorten its vegetative period when the sowing date was delayed, up to its fifth sowing date (corresponding to July). From the seventh sowing date onward, the winter cultivar did not flower before the harvest date of the other treatments. These results partially align with results obtained by Takashima *et al.* (2013), who assessed a narrower range of sowing dates. Furthermore, the winter cultivar accumulated a higher thermal sum for the emergence-flowering period ($p \leq 0.0001$) than the spring cultivar on all sowing dates. In the spring cultivar, the vegetative period expressed in thermal units shortened as the sowing date was delayed (figure 3B page XXX), whereas the winter cultivar displayed a similar trend up to the fifth sowing date (corresponding to July), after which the thermal sum for phenological change significantly increased.



Each point represents the average date of three repetitions. Different letters indicate significant differences between means of treatment.

Cada punto representa la fecha promedio de las tres repeticiones. Letras diferentes indican diferencias significativas entre las medias de los tratamientos.

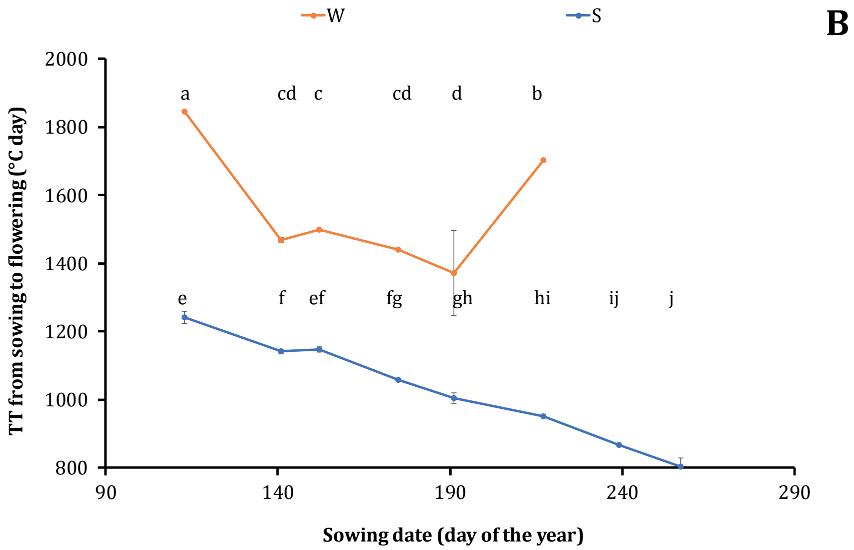


Figure 3. Duration of the Sowing-Flowering period expressed in days **3A** and in thermal time **3B** for two cultivars analyzed (winter in red and spring in blue) and eight sowing dates evaluated expressed according to the day of the year in which sowing took place.

Figura 3. Duración del período siembra - floración expresado en días **3A** y expresado en unidades de tiempo térmico **3B** para los dos cultivares analizados (invernal en rojo y primaveral en azul) y las ocho fechas de siembra evaluadas expresadas según el día del año en que se realizaron.

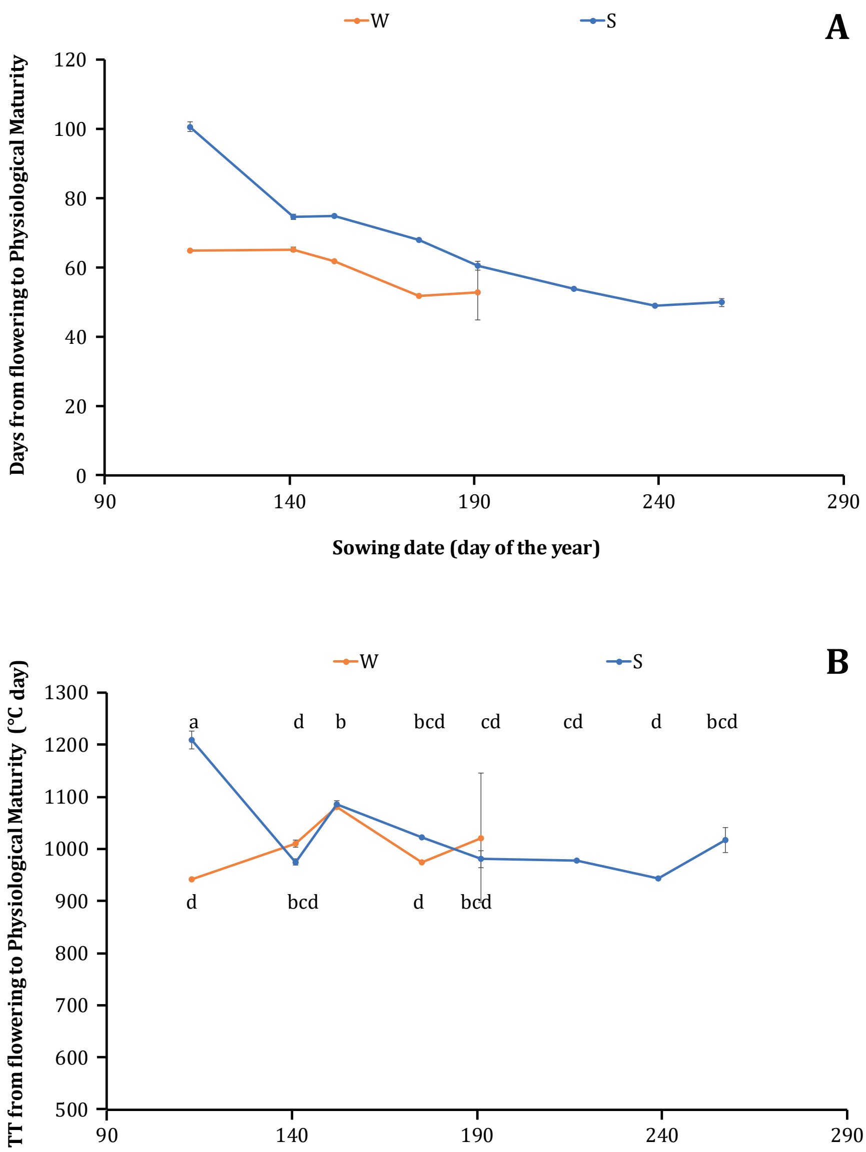
Shortening the vegetative period in the spring cultivar would be compatible with a quantitative photoperiodic effect. In crops with a quantitative response to long-day photoperiod, increases in day length from June 21st to December 21st imply reductions in thermal sums required for growth stage change up to a threshold where the thermal sum is fixed. Since the threshold of approximately 14 hours proposed by Nanda *et al.* (1996) is not reached in the studied sowing dates, inductive photoperiod is not achieved. Hence, the thermal time to flowering was shortened by gradually delaying the sowing date due to the increased day length. At sowing dates where the day length does not exceed 14 hours, changes in day length caused by different sowing dates will be proportional to changes in thermal sum until flowering. In the winter cultivar, starting from the fifth sowing date, thermal sums shift from decreasing with delayed sowing to extending due to their vernalization requirements. Sensitivity to this factor also varies among cultivars (25), and it is unknown what the threshold temperature for vernalization of the analyzed cultivar is or within which period the stimulus is captured. Although cultivars requiring vernalization have accelerated development rates due to temperature accumulation between the range of 4°C to 9°C, the upper defined limit is at 13°C (11). Among plants in which flowering is promoted by the accumulation of cold hours, the effective temperature range is 1-7°C (21). In previous studies on rapeseed varieties, the optimal vernalization temperature was reported within the range of 6-9°C (33). Therefore, sowing winter cultivars after August 5th in the southeastern Buenos Aires region will not allow the accumulation of sufficient cold hours to meet the vernalization requirement for flowering during the growing season.

On the same sowing date, the spring cultivar showed a longer seed-filling duration than the winter cultivar. The duration from flowering to physiological maturity, expressed in days, exhibited an interaction between the sowing date and cultivar type ($p \leq 0.0060$). Both cultivars gradually reduced their filling period duration (figure 4A, page XXX). Significant differences were determined among the combinations of sowing date and cultivar for the duration from the flowering to physiological maturity period expressed in thermal time ($p \leq 0.0013$). The spring cultivar sown in April had the longest seed-filling period, while the remaining combinations of sowing dates and cultivars did not show significant differences in the duration of the period expressed as thermal time, with an approximate value of 1000°C day (figure 4B, page XXX). The findings suggest that the spring cultivar, when sown on the earliest date, may prolong its grain-filling period in thermal time because of occasional frosts during the reproductive phase. This consideration is important because the spring cultivar flowered 50 days earlier than the winter cultivar on the same sowing date (figure 2A, page XXX). The hypothesis regarding the frost effect suggests that the occurrence of frosts may extend grain filling by inducing senescence in main branches, which results in greater development of lateral pods and a delay in crop maturity. It was hypothesized that postponing the sowing date by 20 days after March 1st would decrease the number of frost days by one during the critical period (31).

Crop yield

Sowing dates that resulted in the highest yields were May (date 2) for winter varieties and the end of June (date 4) for spring varieties ($p \leq 0.0001$). For the experimental conditions, an optimal sowing timeframe for both types of rapeseed cultivars was determined to be between late April and July (figure 5, page XXX). Notably, the winter variety failed to flower when sown late, while the spring variety experienced reduced yields due to early frosts when sown too early. Consequently, the highest yields were achieved during a specific flowering window between day 270 and 300 of the year, roughly from mid-September to October, with yields exceeding 5000 kg ha^{-1}. These findings are consistent with prior studies showing increases in grain yields for spring varieties when sowing dates were delayed (15). However, in later sowing dates, the highest yield was associated with the shorter-cycle variety, as observed in a previous study 7. Our findings contrast those previously reported by Agostini (2011), who suggested that environments with longer grain-filling periods would lead to higher returns. Therefore, studying how different cultivar types respond to various environmental variables when sowing dates are adjusted becomes crucial for optimizing critical periods and increasing crop yield (23).

Towards the end of September, the water scenario (figure 1, page XXX), and photothermal conditions improve, and frost incidence decreases, making it the optimal time for the critical period (figure 2B, page XXX). During this period, the photothermal quotient (Q) increases, enhancing radiation capture and allowing for a high accumulation of carbohydrates. The potential photothermal effect suggests that Q could also be used to explain changes in yield in rapeseed, as is the case in various species (3, 6, 9). In addition to the photothermal component, post-flowering rainfall is crucial in rainfed crops and was positively associated with yield and grain oil content (29, 33). Under our experimental conditions, water availability was favorable during October, making it the ideal time for the critical period to take place.

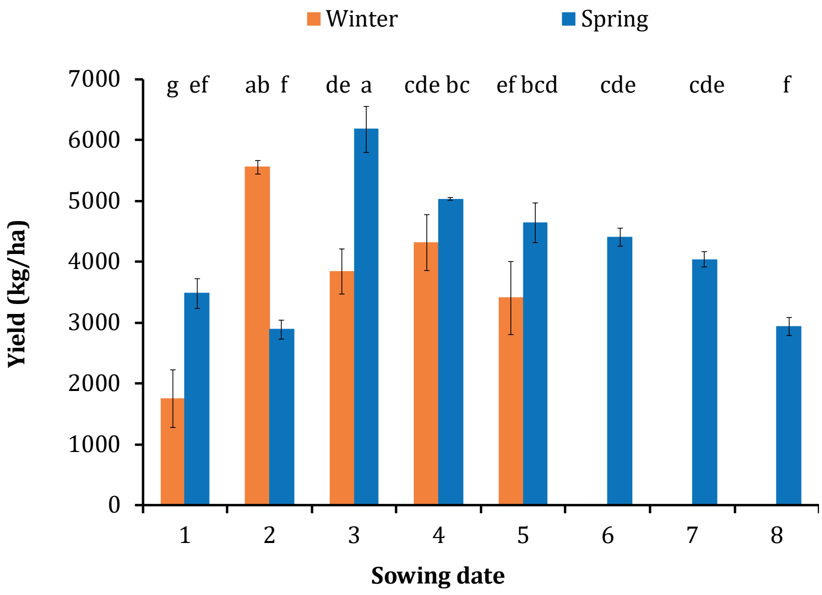


Each point represents the average date of three repetitions. Different letters indicate significant differences between means of treatment.

Cada punto representa la fecha promedio de las tres repeticiones. Letras diferentes indican diferencias significativas entre las medias de los tratamientos.

Figure 4. Duration of the period from Flowering to Physiological Maturity expressed in days **4A** and in thermal time **4B** for two cultivars analyzed (winter in red lines and spring in blue lines) and eight sowing dates evaluated expressed according to the day of the year in which were carried out.

Figura 4. Duración del período de Floración a Madurez Fisiológica expresado en días **4A** y expresado en tiempo térmico **4B** para los dos cultivares analizados (invernal en rojo y primaveral en azul) y las ocho fechas de siembra evaluadas expresadas según el día del año en que se realizaron.



Each point represents the average data of three repetitions. Different letters indicate significant differences between means of treatments (P<0.05).

Cada barra representa el rendimiento promedio de las tres repeticiones y su error estándar. Letras diferentes indican diferencias significativas entre las medias de los tratamientos (P<0,05).

Figure 5. Grain yield expressed in kilograms per hectare on a dry basis for the two cultivars analyzed (winter in orange and spring in blue) and the eight sowing dates evaluated.

Figura 5. Rendimiento expresado en kilogramos por hectárea en base seca para los dos cultivares analizados (invernal en naranja y primaveral en azul) y las ocho fechas de siembra evaluadas.

In summary, variations in sowing dates and cultivar selection influenced the timing of the critical period. Alterations in sowing dates resulted in shifts in the flowering date, ranging from day 200 to day 300, thus delaying the flowering period from June to approximately October. The optimal sowing dates identified in this research differ slightly from those recommended for no-tillage systems in the region, which typically occur in March and April. The study was conducted under conventional tillage in only one season, potentially mitigating frost damage during crop emergence with sowing dates after May. Winter cultivars show less flexibility in sowing dates than spring varieties, as they may not flower in late sowings due to the absence of vernalization conditions. For the evaluated experimental conditions, the only observed limitation in the sowing date of spring cultivars is to avoid planting before April due to the high risk of frequent frost during the flowering period.

Conclusion

Changes in sowing date presented differences in both location and duration of vegetative and reproductive stages, tending to shorten their cycle. However, in late sowing, winter cultivars lengthened their cycle to the point of not reaching flowering during the growing season. For the tested environmental experiment conditions, optimal sowing dates were between the end of April and July for both spring and winter cultivars.

References

1. Agosti, M. B. 2011. Fertilización nitrógeno-azufrada y variabilidad genotípica en el rendimiento y la calidad del grano en colza-canola (*Brassica napus* L.). Tesis Magister. Universidad de Buenos Aires. 130 p.
2. Allen, R. G.; Pereira, L. S.; Raes, D.; Smith, M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper N° 56. FAO. Rome. Italy. 300 p.

3. Arisnabarreta, S.; Miralles, D. J. 2008. Critical period for grain number establishment of near isogenic lines of two- and six-rowed barley. Field Crops Research. 107: 196-202. https://doi.org/10.1016/j.fcr.2008.02.009
4. Arnoud, F. 1989. Colza: selection, varietés. Cahier Technique. CETIOM. París, Francia. 28 p.
5. Bouché, F.; Woods, D. P.; Amasino, R. M. 2017. Winter memory throughout the plant kingdom: Different paths to flowering. Plant Physiology. 173(1): 27-35. https://doi.org/10.1104/pp.16.01322
6. Cantagallo, J. E.; Chimenti, C. A.; Hall, A. J. 1997. Number of seed per unit area in sunflower correlates well with a phototermal quotient. Crop Science. 37: 1780- 1786. https://doi.org/10.2135/cropsci1997.0011183X003700060020x
7. Coll, L.; Larrosa, L. M. 2010. Efecto de la fecha de siembra y el ciclo sobre el rendimiento de colza. Actualización Técnica N° 1. EEA INTA Paraná. 36 p.
8. Di Rienzo, J. A.; Casanoves, F.; Balzarini, M. G.; Gonzalez, L.; Tablada, M.; Robledo, C. W. 2008. InfoStat, Grupo InfoStat. FCA. Universidad Nacional de Córdoba. Argentina.
9. Fischer, R. A. 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. Journal of Agriculture Science. Cambridge. 105: 447-461. https://doi.org/10.1017/S0021859600056495
10. Gómez, N. V.; Miralles, D. J. 2011. Factors that modify early and late reproductive phases in oilseed rape (*Brassica napus* L.): Its impact on seed yield and oil content. Industrial Crops and Products. 34: 1277-1285. https://doi.org/10.1016/j.indcrop.2010.07.013
11. Gómez, N. V.; Miralles, D. J.; Mantese, A. I.; Menéndez, Y. C.; Rondanini, D. P. 2018. Colza: un cultivo con historia en la FAUBA. Universidad de Buenos Aires. Facultad de Agronomía; Agronomía & Ambiente. 38(1): 23-36.
12. Habekotté, B. 1997. Evaluation of seed yield determining factors of winter oilseed rape (*Brassica napus* L.) by means of crop growth modelling. Field Crops Research. 54: 137-151. https://doi.org/10.1016/S0378-4290(97)00044-0
13. Hocking, P. J.; Kirkegaard, J. A.; Angus, J. F.; Gibson, A. H.; Koetz, E. A. 1997. Comparison of canola, Indian mustard and Linola in two contrasting environments. I. Effects of nitrogen fertilizer on dry-matter production, seed yield and seed quality. Field Crops Research. 49: 107-125. https://doi.org/10.1016/S0378-4290(96)01063-5
14. Iriarte, L. B. 2014. Cultivo de colza: fecha de siembra, densidad y distancia entre surcos. INTA Barrow. 11 p.
15. Iriarte, L. B.; Valetti, O. 2008. Cultivo de Colza. INTA. Buenos Aires. 152 p.
16. Iriarte, L. B.; López, Z. B. 2014. El cultivo de colza en Argentina. Situación actual y perspectivas. 1° Simposio Latinoamericano de Canola. Passo Fundo. Brasil. 1-7.
17. Kirkegaard, J. A.; Lilley, J. M.; Berry, P. M.; Rondanini, D. P. 2021. Canola. In: Sadras VO and Calderini DF. Crop Physiology Case Histories for Major Crops, eds and (Academic Press). 518-549.
18. Lin, L.; Allemekinders, H.; Dansby, A.; Campbell, L.; Durance-Tod, S.; Berger, A.; Jones, P. J. 2013. Evidence of health benefits of canola oil. Nutr. Rev. 71: 370-385. https://doi.org/10.1111/nure.12033
19. McWilliam, S. C.; Stafford, J. A.; Scott, R. K.; Norton, G.; Stokes, D. T. 1995. The relationship between canopy structure and yield in oilseed rape. In: Proceedings of the 9th International Rapeseed Congress. Cambridge. UK. 491-493.
20. Mendham, N. J.; Salisbury, P. A. 1995. Physiology: crop development, growth and yield. In: Kimber D.; McGregor, D. I. (Eds.), Brassica Oilseed, Production, Utilization, Camb. 11-64.
21. Michaels, S.; Amasino, R. 2000. Memories of winter: vernalization and the competence to flower. Plant Cell Environ. 23: 1145–1154. https://doi.org/10.1046/j.1365-3040.2000.00643.x
22. Mingeau, M. 1974. Comportement du colza e printemps a la sécheresse. Informations Techniques (Paris, France). 36: 1-11.
23. Miralles, D. J.; Ferro, B.; Slafer, G. 2001. Developmental responses to sowing date in wheat, barley and rapeseed. Field Crops Research. 71: 211-223. https://doi.org/10.1016/S0378-4290(01)00161-7
24. Morrison, M. J.; Stewart, D. W. 2002. Heat stress during flowering in summer brassica. Crop Science. 42: 797-803. https://doi.org/10.2135/cropsci2002.7970
25. Murphy, L.; Scarth, R. 1991. Vernalization response of spring canola (*Brassica napus* L.) In: Mc Gregor DI (eds.). Proceedings of the Eight International Rapeseed Congress. Saskatoon, Saskatchewan. Canadá. 1764-1768.
26. Nanda, R.; Bhargava, S.; Tomar, D.; Rawson, H. M. 1996. Phenological development of *Brassica campestris*, *B. juncea*, *B. napus* and *B. carinata* grown in controlled environments and from 14 sowing dates in the field. Field Crops Res. 46: 93-103. https://doi.org/10.1016/0378-4290(95)00090-9
27. Permingeat, M. P. 2013. Rendimiento de colza 00: determinación del período crítico. Tesis de grado. Facultad de Ciencias Agrarias. Universidad de Mar del Plata. Argentina. 20 p.
28. Rondanini, D. P.; Menendez, Y. C.; Gomez, N. V.; Miralles, D. J.; Botto, J. F. 2017. Vegetative plasticity and floral branching compensate low plant density in modern spring rapeseed. Field Crops Research. 210: 104-113. https://doi.org/10.1016/j.fcr.2017.05.021
29. Secchi, M. A.; Fernandez, J. A.; Stamm, M. J.; Durrett, T.; Prasad, P. V. V.; Messina, C. D.; Ciampitti, I. A. 2023. Effects of heat and drought on canola (*Brassica napus* L.) yield, oil, and protein: a meta-analysis. Field Crops Res. 293. Article 108848. 10.1016/j. fcr.2023.108848

30. Silvester-Bradley, R.; Makepeace, R. J. 1984. A code for stages of development in oilseed rape (*Brassica napus* L.). Aspects of Applied Biology. 6: 399-419.
31. Takashima, N. E.; Rondanini, D. P.; Puhl, L. E.; Miralles, D. J. 2013. Environmental factors affecting yield variability in spring and winter rapeseed genotypes cultivated in the southeastern Argentine Pampas. European Journal of Agronomy. 48: 88-100. https://doi.org/10.1016/j.eja.2013.01.008
32. Tommey, A. M.; Evans, E. J. 1991. Temperature and daylength control of flower initiation in winter oilseed rape (*Brassica napus* L.). Annals of Applied Biology. 118: 201-208. https://doi.org/10.1111/j.1744-7348.1991.tb06098.x
33. Walton, G.; Si, P.; Bowden, B. 1999. Environmental impact on canola yield and oil. In: Proceedings of the 10th International Rapeseed Congress. Camberra, Australia. http://www. regional.org.au/au/gcirc/2/136.htm (Accessed: Sept 2023).
34. Weymann, W.; Bottcher, U.; Sieling, K.; Kage, H. 2015. Effects of weather conditions during different growth phases on yield formation of winter oilseed rape. Field Crops Res. 173: 41-48. https://doi.org/10.1016/j.fcr.2015.01.002
35. Woźniak, E.; Waszkowska, E.; Zimny, T.; Sowa, S.; Twardowski, T. 2019. The rapeseed potential in Poland and Germany in the context of production, legislation, and intellectual property rights. Front Plant Sci. 2019 Nov 5;10:1423. doi: 10.3389/fpls.2019.01423. PMID: 31749825; PMCID: PMC6848278.
36. Yaniv, Z.; Schafferman, D.; Zur, M. 1995. The effect of temperature on oil quality and yield parameters of high- and low-erucic acid Cruciferae seeds (rape and mustard). Industrial Crops and Products. 3: 247-251. https://doi.org/10.1016/0926-6690(94)00041-V
37. Zhang, Z.; Cong, R. H.; Ren, T.; Li, H.; Zhu, Y.; Lu, J. W. 2020. Optimizing agronomic practices for closing rapeseed yield gaps under intensive cropping systems in China. Journal of Integrative Agriculture. 19(2020): 1241-1249. https://doi.org/10.1016/S2095-3119(19)62748-6
38. Zheng, Q.; Liu, K. 2022. Worldwide rapeseed (*Brassica napus* L.) research: A bibliometric analysis during 2011-2021. Oil Crop Science. 7(4): 157-165. https://doi.org/10.1016/j.ocsci.2022.11.004.

Conflict of interest

The authors declare the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.