SEMINA
Ciências Agrárias

DOI: 10.5433/1679-0359.2025v46n2p639

Thermal requirements and impacts of chilling accumulation on the phenology of olive (*Olea europaea* L.) cultivars in Southern Brazil

Exigências térmicas e impactos do acúmulo de frio na fenologia de cultivares de oliveira (*Olea europaea* L.) no Sul do Brasil

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Highlights

A negative correlation exists between chilling and heat accumulation.
Insufficient chilling leads to early budburst and flowering in olive cultivars.
Flowering in cold-requiring cultivars, e.g., 'Picual,' is affected by warm winters.

Abstract

Chilling and thermal heat requirements play fundamental roles in the phenological cycle of olive trees (*Olea europaea* L.) by impacting the initiation of budburst, flowering, and productivity. In this study, we evaluated the thermal requirements of four olive cultivars, 'Arbequina,' 'Koroneiki,' 'Picual,' and 'Arbosana,' in the Campanha region of Rio Grande do Sul, Brazil, over eight phenological cycles (2015/2016 to 2023/2024). We determined the timing and duration of the budburst and flowering stages for these cultivars and also analyzed their chilling hour (CH), chilling unit (CU), and accumulated thermal sum (STa) requirements. The results revealed that chilling accumulation ranged from 136–419 CHs, whereas STa ranged from 61.50–161.40 °C.day^{-1} for budburst and from 110.98–242.80 °C.day^{-1} for flowering. Early cultivars, such as 'Arbequina' and 'Koroneiki,' exhibited lower chilling requirements and higher STa, whereas 'Picual' required greater chilling accumulation and lower STa. Principal component analysis revealed correlations between variables, demonstrating that mild winters anticipated phenological events. A negative correlation was observed between chilling and heat accumulation, and insufficient chilling compromised flowering synchrony, with potential effects on pollination and production. Early cultivars were more suited to mild winters than late cultivars, whereas late cultivars, e.g., 'Picual,' were more vulnerable to climate change. Our findings highlight the importance of adapting olive tree

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Received: Oct. 06, 2024 Approved: Mar. 06, 2025

management to local conditions and choosing suitable cultivars to ensure adequate productivity in emerging subtropical regions.
Key words: *Olea europaea* L. Cumulative thermal sum. PCA. Subtropical. Chilling requirement.

Resumo

As exigências térmicas de frio e calor desempenham um papel fundamental no ciclo fenológico da oliveira (*Olea europaea* L.), influenciando o início da brotação, a floração e a produtividade. Este estudo avaliou as exigências térmicas de quatro cultivares de oliveira - Arbequina, Koroneiki, Picual e Arbosana- na região da Campanha do Rio Grande do Sul, Brasil, ao longo de oito ciclos fenológicos (2015/2016 a 2023/2024). Foram determinados os estádios de brotação e floração, além de analisadas as horas de frio (HF), unidades de frio (UF) e a soma térmica acumulada (STa) para cada cultivar. Os resultados mostraram que o acúmulo de frio variou de 136 a 419 HF, enquanto a STa variou de 61,50 °C.dia^{-1} a 161,40 °C.dia^{-1} para brotação, e de 110,98 °C.dia^{-1} a 242,80 °C.dia^{-1} para floração. Cultivares precoces, como Arbequina e Koroneiki, apresentaram menor exigência em frio e maior STa, enquanto 'Picual' demandou maior acúmulo de frio e menor STa. A análise de componentes principais revelou correlações entre as variáveis, evidenciando que invernos amenos anteciparam os eventos fenológicos Os resultados evidenciam uma correlação negativa entre acúmulo de frio e calor. A insuficiência de frio comprometeu a sincronia da floração, com impactos potenciais na polinização e produção. As cultivares precoces mostraram-se mais adequadas a invernos amenos, enquanto cultivares tardias, como 'Picual', podem ser mais vulneráveis às mudanças climáticas. Este estudo destaca a importância de adaptar o manejo da oliveira às condições locais e à escolha de cultivares adequadas para garantir a produtividade em regiões subtropicais emergentes.
Palavras-chave: *Olea europaea* L. Soma térmica acumulada. PCA. Subtropical. Exigência de frio.

The thermal requirements for chilling and heating play crucial roles in the growth and development of olive trees. The accumulation of chilling, necessary for the initiation of budburst and flowering, directly impacts the number and quality of inflorescences (Rojo et al., 2020). After meeting the chilling requirement, accumulated thermal sum (STa) becomes essential for the completion of phenological stages, which affects the duration of the plant cycle and helps in estimating maturation and harvesting, which, in turn, are essential factors for crop management and production optimization (Rubio-Valdés et al., 2022).

Most studies on these thermal requirements have been conducted in Mediterranean climate regions. However, olive phenology and productivity can vary significantly in climates other than those typical of the Mediterranean region (Medina-Alonso et al., 2020; Dias et al., 2022). With the expansion of olive cultivation in Brazil, mainly in Rio Grande do Sul, which is currently the main producer, it is necessary to determine the thermal requirements of this crop in the region. Rio Grande do Sul has approximately 6.000 ha planted and is responsible for 75% of the national olive oil production (Instituto Brasileiro de Olivicultura [IBRAOLIVA], 2024).

However, little research has been conducted on the thermal requirements of olive trees in subtropical regions, such as southern Brazil. Herein, we aimed to determine the thermal requirements of a few main olive cultivars in the Campanha region of Rio Grande do Sul and evaluate how the accumulation of chilling and heat impacts budburst and flowering periods, contributing to the knowledge regarding the adaptation of the crop to these climatic conditions.

The experiment was performed in Dom Pedrito (31°08'46.71" S, 54°11'53.80" W at an altitude of 378 m) under a humid subtropical climate (Köppen, 1931). Four olive cultivars (*Olea europaea* L.), 'Arbequina,' 'Koroneiki,' 'Picual,' and 'Arbosana,' planted in 2010 with a spacing of 7 m × 5 m between rows and plants and grown in a polyconic system, were evaluated.

The phenology was evaluated over eight cycles from 2015/2016 to 2023/2024. The following stages were determined: budburst (31; 37) and flowering (61; 69) following the Biologische Bundesanstalt Bundessortenamt, Chemische Industrie (BBCH) scale developed for olive trees (Sanz-Cortés et al., 2002). The study duration was described in days on the civil calendar.

The chilling requirements were calculated based on two factors: chilling hours (CHs) and chilling units (CUs). Counting started on April 1 and continued until the budburst date. For estimating CHs, the hourly mean temperatures ≤7.2 °C were added. CUs were calculated using the Model 1 of De Melo-Abreu et al. (2004). The hourly temperature data used were obtained from the meteorological stations of the National Institute of Meteorology, located in Dom Pedrito, Rio Grande do Sul (31°09'6.38" S, 54°37'12.30" W).

STa was obtained by adding degree days (GD), calculated using the model of Ometto (1981), for each phenological stage and olive cultivar. Daily temperature data (°C) were obtained from a meteorological station in the study area.

Principal component analysis (PCA) was performed to detect possible clusters among the dependent variables. A biplot graph was constructed with the first and second principal components using the Fitopac software (version 2.1).

Table 1 shows the interannual variability over the eight phenological cycles. The CH ranged from 136 (2023/2024) to 419 (2018/2019), whereas the CU ranged from 459 to 1197 during the same period. The budburst initiation dates were between July 1 (2023/2024) and September 4 (2018/2019), and flowering ranged from September 2 (2023/2024) to October 1 (2018/2019).

The PCA results (Figure 1A) revealed that the analyzed cycles were dispersed, forming three distinct clusters. The 2016/2017, 2018/2019, and 2019/2020 cycles were positively aligned with Dim1 (67.97%), indicating greater chilling accumulation and later phenology. In contrast, the 2015/2016 and 2023/2024 cycles were negatively correlated with Dim1, indicating warmer winters and earlier phenological events. The 2020/2021, 2021/2022, and 2022/2023 cycles were positioned intermediately, negatively to Dim2 (20.94%), forming the third group and exhibiting less accentuated variations than the other cycles.

These results indicate that insufficient chilling accumulation may compromise compliance with chilling requirements, resulting in early budburst and flowering (Elloumi et al., 2020). Another possibility is that the low chilling requirements of olive trees were met in the study region, and the increase in temperature may have contributed to the precocity of these phenological stages (Orlandi et al., 2004).

The STa for budburst ranged from 61.50 °C.day^{-1} (2021/2022) to 161.40 °C.day^{-1} (2023/2024); however, for flowering, it was 110.98 °C.day^{-1} (2022/2023) to 242.80 °C.day^{-1} (2023/2024) (Table 1). In the cycles of low chilling accumulation, the anticipation of budburst and flowering was accompanied by a higher STa (Figure 1A), revealing a negative correlation between chilling accumulation and the thermal sum required to complete the phenological stages.

This pattern was also observed in other cultivars. The earliest cultivars, 'Arbequina' and 'Koroneiki,' with budbursts on August 2 and flowering between September 15 and 17, exhibited the lowest chilling accumulation (281 and 304 CHs, respectively; 779 and 813 CUs, respectively) and the highest STa (106.56 and 111.18 °C.day^{-1} for budburst, respectively; 185.22 and 191.82 °C.day^{-1} for flowering, respectively). In contrast, 'Picual' was the latest, with budburst on August 17 and flowering on October 3, with the highest chilling requirement (352 CHs and 911 CUs) and the lowest STa (65.90 °C.day^{-1} for budburst and 120.68 °C.day^{-1} for flowering) (Table 1).

Abou-Saaid et al. (2022) also identified a negative correlation between chilling and heat accumulation, indicating that enhanced chilling accumulation reduces the heat requirement. In contrast, Elloumi et al. (2020) reported a positive correlation between chilling and heat accumulation, suggesting that local factors and cultivar-specific characteristics may impact this relationship.

The duration of the phenological stages followed these variations, with budburst lasting from 8 d (2021/2022) to 17 d (2023/2024) and flowering from 16 d (2016/2017) to 42 d (2023/2024) (Table 1). The prolongation of these stages correlated with low chilling accumulation and increased STa in the PCA results (Figure 1A). Medina-Alonso et al. (2020) reported that insufficient winter chilling in Tenerife resulted in early and prolonged flowering; however, the increased STa may be related to the need for relatively more time to accumulate the heat necessary to complete the phenological stages (Murray et al., 1989).

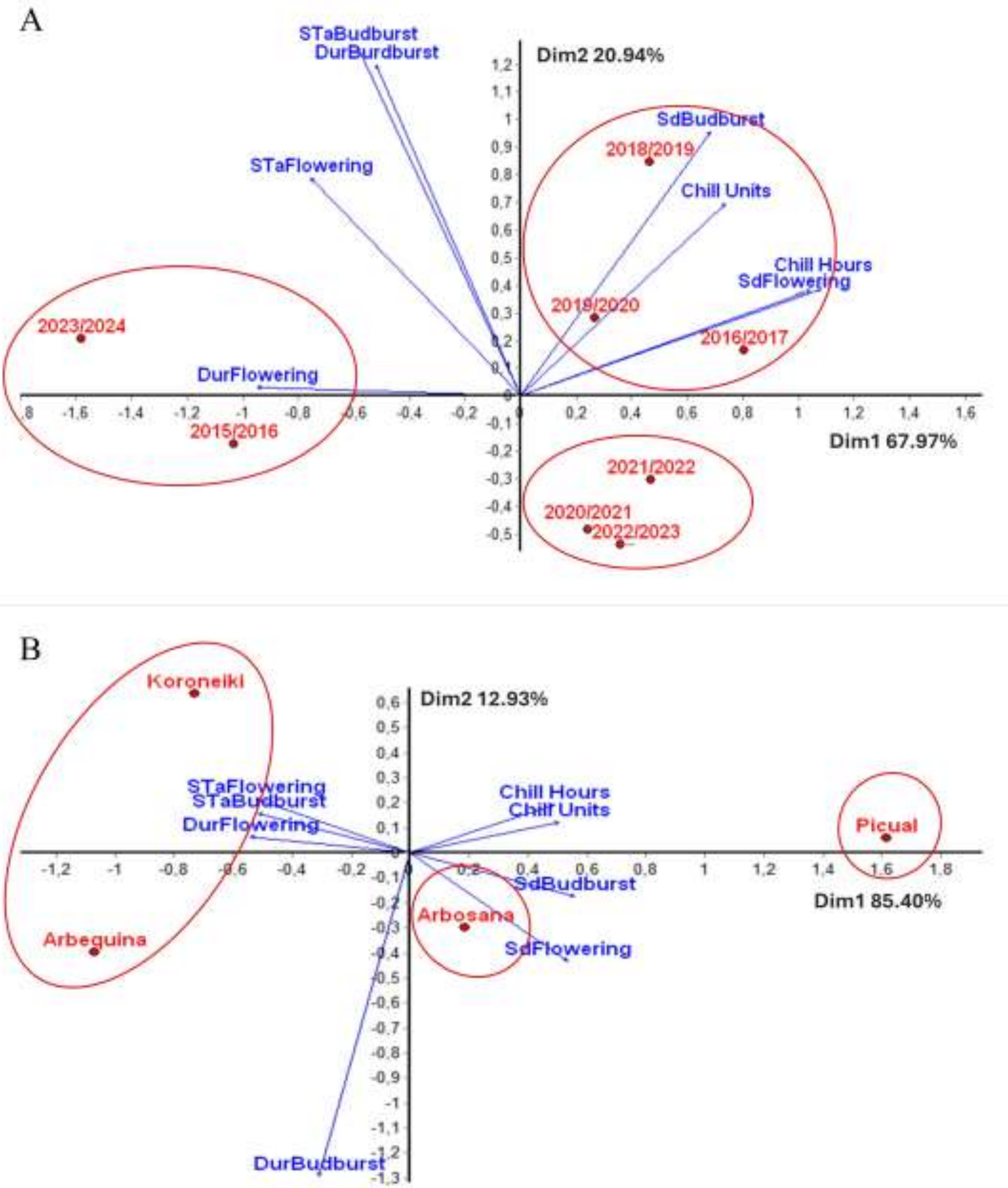

Figure 1. Principal component analysis (PCA) results based on the impacts of chill accumulation (chill hours and chill units) across eight evaluation cycles (A) and four olive cultivars (B). Abbreviations: SdBudburst, the start date of budburst; DurBudburst, duration of budburst; STaBudburst, thermal sum of budburst; SdFlowering, the start date of flowering; DurFlowering, duration of flowering; and StaFlowering, thermal sum of flowering.

Table 1
Chilling hours, chilling units, accumulated thermal sum (STa), and duration of phenological stages (budburst and flowering) for eight cycles and four olive cultivars

Cycles	Chilling Requirements	
	Chilling Hours (CH)	Chilling Units (CU)
2015/2016	298	661
2016/2017	415	1.068
2018/2019	419	1.197
2019/2020	411	940
2020/2021	332	815
2021/2022	381	847
2022/2023	356	831
2023/2024	136	459

Development Stages	Cycles	Phenology and Heat Requirements		
		Start Date	Duration (days)	STa (°C.day^{-1})
Budburst	2015/2016	July 25	10	136.90
	2016/2017	August 25	11	101.02
	2018/2019	September 04	14	109.90
	2019/2020	August 26	12	98.90
	2020/2021	July 29	9	70.80
	2021/2022	August 02	8	61.50
	2022/2023	August 02	9	72.65
	2023/2024	July 01	17	161.40
Flowering	2015/2016	September 04	40	220.10
	2016/2017	September 30	16	112.20
	2018/2019	October 01	22	198.32
	2019/2020	September 23	28	187.48
	2020/2021	September 19	24	123.80
	2021/2022	September 30	21	180.42
	2022/2023	September 22	23	110.98
	2023/2024	September 02	42	242.80

Cultivars	Chilling Requirements	
	Chilling Hours (CH)	Chilling Units (CU)
Arbequina	281	779
Koroneiki	304	813
Picual	352	911
Arbosana	323	853

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Development Stages	Cycles	Phenology and Heat Requirements		
		Start Date	Duration (days)	STa (°C.day⁻¹)
Budburst	Arbequina	August 02	12	106.56
	Koroneiki	August 02	9	111.18
	Picual	August 17	9	65.90
	Arbosana	August 09	11	97.42
Flowering	Arbequina	September 17	30	185.22
	Koroneiki	September 15	29	191.82
	Picual	October 03	17	120.68
	Arbosana	September 28	24	162.62

Elucidating the chilling requirements of cultivars is necessary to determine suitable planting areas and assess precocity. In this study, 'Arbequina' and 'Koroneiki' were negatively positioned in Dim1 (85.40%), indicating lower chilling requirements than those of the other cultivars and early phenology. In contrast, 'Picual' stood out positively, confirming higher chilling requirements than those of the other cultivars and late phenological cycles, whereas 'Arbosana' exhibited an intermediate behavior and was positioned negatively in Dim2 (12.93%), suggesting a moderate response to climatic conditions (Figure 1B). These results, consistent with those of Melo-Abreu et al. (2004), revealed genetic differences between the cultivars, suggesting that 'Arbequina' and 'Koroneiki' are relatively more suitable for regions with mild winters, whereas 'Picual' may not be ideal for high-temperature regions.

In recent years, climate change, marked by warmer springs, has altered the flowering time of olive trees (Ozdemir, 2016). In the present study, the 'Picual' cultivar, which exhibited the highest chilling requirement among those evaluated, showed not only delayed flowering but also a shorter flowering duration, as shown in Table 1, with only 17 d of flowering, nearly 13 d less than that of the early cultivars. This short flowering period can impair pollination and, consequently, fruit set, affecting production.

Elucidating the effects of chilling accumulation on the phenological cycle of olive trees in regions where this crop is expanding is of great relevance, particularly because of climate change. Winter chilling accumulation is essential for budburst, a sensitive phase that can be impaired by late frost or heat waves (Rojo et al., 2020). Additionally, chilling accumulation influences the timing of flowering, which determines whether a cultivar flowers early or late. Early cultivars can flower during high spring rainfall, whereas late cultivars can flower during high temperatures (Navas-Lopez et al., 2019). Flowering synchronization among olive cultivars is important when cross-pollination is necessary and can improve productivity (Maniriho, 2022).

The results obtained in this study revealed that low chilling accumulation exerted a significant effect on olive phenology by inducing early budburst and flowering in all cultivars evaluated. A negative correlation was identified between chilling and the heat accumulation necessary to complete these phenological stages. Cultivars such as Arbequina and Koroneiki exhibited the lowest chilling requirements, whereas 'Picual' demonstrated the highest among the evaluated cultivars. These results emphasize the importance of adjusting olive tree management based on the chilling accumulation requirements of each cultivar.

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