International Journal of Horticultural Science and Technology
Journal homepage: http://ijhst.ut.ac.ir

A Study of Chill and Heat Requirements of Resilient Apricot (*Prunus armeniaca*) Varieties in Response to Climate Change

Kaouther Boutiti[1]*, Ines Bellil[1], Douadi Khelifi[2]

1 Laboratoire de Génétique, Biochimie et Biotechnologies Végétales, Faculté des Sciences de la Nature et de la Vie, Université Frères Mentouri Constantine 1, Constantine, 25000, Algeria
2 École Nationale Supérieure de Biotechnologie, Pôle Universitaire, Constantine, 25000, Algeria

ARTICLE INFO

Article history:

Received: 16 March 2024,
Received in revised form: 3 June 2024,
Accepted: 19 June 2024

Article type:

Research paper

Keywords:

Chill requirement,
Climate change,
Dynamic models,
Heat requirement,
Prunus armeniaca

ABSTRACT

The predicted climatic scenarios for Mediterranean regions present specific challenges to agricultural production. In Algeria, apricot production has been consistently declining, with both the quality and quantity of fruit significantly affected by genotype-environment interactions. This research aimed to investigate the chill and heat requirements related to apricot flowering to identify superior cultivars with desirable traits—specifically, low chill and high heat requirements—for use in a breeding program. Eighteen cultivars were selected to assess their chill and heat requirements over two consecutive years (2021-2022). Universal mathematical models, including the Dynamic Model, Utah Model, and Chill Hours below 7 °C, were employed to quantify the chill requirements. Meanwhile, the Growing Degree Hours (GDH) model was used to measure the heat requirements essential for apricot flowering. Significant differences in chill and heat requirements were observed among the apricot cultivars, which were classified into three groups based on their chill requirements (low, medium, and high), ranging from 26 to 72 Chill Portions (CP). The heat requirements for flowering ranged from 1,574 to 5,597 GDH. This variability enabled us to identify five cultivars with low chill requirements (Khad Romia, Bedai, Boufarik, Bish, and Monte) as potential candidates for future apricot breeding programs.

Abbreviation: Analysis of Variance (ANOVA), Date of Breaking dormancy (BD), Chill hours (CH), Chill Portion (CP), Chill Requirements (CR), Coefficient of Variation (CV%), Chill Units (CU), 50% of Flowering (F50), Flowering Date (FD), Growing Hours Degree (GDH), Heat Requirements (HR), Standard of deviation (SD).

Introduction

Fruit trees that thrive in temperate climates naturally flourish in regions with cold winters and distinct seasonal shifts, providing optimal conditions for growth during the spring and summer seasons (Pio et al., 2019). These trees constitute approximately 48% of global fruit production and serve as a vital source of sustenance, significantly contributing to the economic well-being of farmers (Rodríguez et al., 2021). Among these temperate fruits are stone fruit trees such as *Prunus armeniaca* (apricot), *Prunus mume* (Japanese apricot), *Prunus domestica* L. (European plum), *Prunus salicina* Lindl. (Japanese plum), *Prunus persica* L. Batsch (peach), *Prunus cerasus* L. (sour cherry), and

*Corresponding author's email: kaoutherboutiti@gmail.com

Prunus avium L. (sweet cherry) (Fadón et al., 2020b).
The apricot tree, originating from China and Central Asia, has been cultivated across various continents, including Asia, Europe, Oceania, Africa, North America, and South America (Wang et al., 2022). As one of the most widely cultivated fruit trees within the *Prunus* genus (Venturi et al., 2022), the apricot holds a prominent position in global fruit production. Notably, Algeria ranks among the top ten apricot-producing nations, with an annual yield of 189,724 tons (https://www.fao.org/faostat/en/#data/QV).
The apricot tree is known for its adaptability to Mediterranean climates (Bourguiba et al., 2012) and demonstrates significant resilience against cold winter temperatures (Bassi et al., 2006). To protect sensitive developing tissues from the cold, fruit trees in temperate climates shed their leaves during the cold season, followed by the accumulation of winter chill to initiate dormancy (endo-dormancy, para-dormancy, and eco-dormancy) (Egea et al., 2020). This dormancy phase serves as a period of rest, enabling the tree to withstand external stresses during winter cycles (Andreini et al., 2014), which are induced by factors such as short photoperiods and temperature decreases leading to meristem inactivation (Campoy et al., 2011b). Dormancy ends when a sufficient amount of chill has accumulated, prompting buds to flower in response to the warmth during the vegetative period (Andreini et al., 2014).
Several models have been proposed to calculate chilling and heat accumulation based on temperature measurements between specific thresholds over time. These include the Chilling Hours model, the Utah model, the Dynamic model for chilling requirements, and the Growing Degree Hours (GDH) model for heating requirements. The Chilling Hours model is the oldest and most commonly used method for calculating winter cold, assuming that all hours with temperatures between 0 and 7 °C are equally effective for the accumulation of winter chill (Weinberger, 1950). In contrast, the Utah model assigns different cooling rates to various temperature ranges, including the negative contributions of high temperatures (Richardson et al., 1974). The Dynamic model, intended for warm winters, calculates chill requirements by assuming a two-stage process: the formation of a precursor cooling compound in flowering buds, favored by cold temperatures, and the subsequent transformation into a permanent chill portion when a certain threshold is reached, despite potential destruction by high temperatures (Fishman et al., 1987b, 1987a). Numerous studies on fruit trees, including apricot, peach, and apple, have reported on the estimation of chilling and heating requirements (Gao et al., 2012; Guo et al., 2014, 2015; Maulión et al., 2014; Ruiz et al., 2007; Ruml et al., 2018; Zhuang et al., 2016). Estimating these requirements is essential for assisting farmers in selecting appropriate varieties for their orchards (Fadón et al., 2020a). Chill and heat requirements vary not only between species but also among cultivars within the same species (Fadón et al., 2020a). Given the specific climatic needs of these fruit trees, selecting suitable cultivars for a particular area is crucial for achieving sustainable production levels (Rodríguez et al., 2021).
The agricultural sector is facing distinct challenges in response to projected climatic scenarios for Mediterranean regions, particularly due to rising temperatures and increased ultraviolet radiation. These changes pose significant economic and nutritional challenges by disrupting the life cycle of fruit trees (Ali et al., 2023b, 2023a). Resulting abiotic stresses affect the phenology of fruit-bearing trees such as apple, pear, peach, plum, apricot, cherry, olive, and almond, leading to undesirable physiological changes such as abnormal bud burst, advanced or delayed flowering, interrupted fruit growth and ripening, advanced leaf senescence, and fruit abscission (Ramírez and Kallarackal, 2015; Salama et al., 2021). Climatic changes can alter the adaptability and sustainability of temperate fruit trees in their growing areas (Salama et al., 2021), prompting scientists to develop strategies to enhance the adaptability of trees to climatic changes. These strategies include various plant breeding methods such as mutation breeding (rice) (Ali et al., 2019), molecular marker-assisted selection (apricot, peach, apple) (Dirlewanger et al., 2004, 2009), and gene editing (apple) (Nishitani et al., 2016).
Algeria, located within the warm Mediterranean climatic zone, is increasingly vulnerable to the effects of climate change. Experts predict a significant rise in temperature by 2°C, coupled with a 10 to 15% decrease in precipitation. Additionally, the frequency of droughts is expected to increase, along with more intense rainfall patterns in the foreseeable future (Sahnoune et al., 2013). Climate change, particularly through the steady increase in mean temperatures (Shivanna, 2022), has a profound impact on ecological balance, ecosystem dynamics—including shifts in typical meteorological patterns—and socio-economic aspects, leading to challenges in adaptive capacities and food security (Muluneh, 2021).
Monitoring plant phenological patterns in a

controlled environment, such as estimating chill and heat requirements across various cultivars, is a valuable tool for predicting the future performance of orchards. This approach aids in selecting appropriate varieties with either early or late flowering times, which is crucial for breeding programs. Such insights are essential for selecting cultivars with traits that help mitigate the impacts of climate change (Campoy et al., 2012; Fadón et al., 2020a; Mahmoud, 2016; Pantelidis and Drogoudi, 2023; Zhang et al., 2023). Low cold tolerance is critical for better adaptation to hot climates, while high heat tolerance is necessary to reduce the risk of early blooming and subsequent frost damage.

In this study, the cold and heat requirements related to flowering times were measured across 18 apricot cultivars using three distinct models. Various methods for assessing chill requirements were also compared and analyzed. The relationships between cold and heat requirements and flowering dates were investigated. The findings significantly contribute to refining apricot cultivation practices, providing valuable insights into the cold and heat requirements of different apricot varieties and their flowering times. Moreover, this research will enhance the selection process for cultivars with desirable traits, supporting breeding programs aimed at adapting to changing climatic conditions.

Material and Methods

The plant materials used were collected from private orchards situated in four Algerian provinces (Constantine, M'sila, Batna, and Biskra), each characterized by distinct climatic conditions, including arid, semi-arid, and hot-desertic and geographic regions (Fig. 1). The study consisted of 18 apricot cultivars.

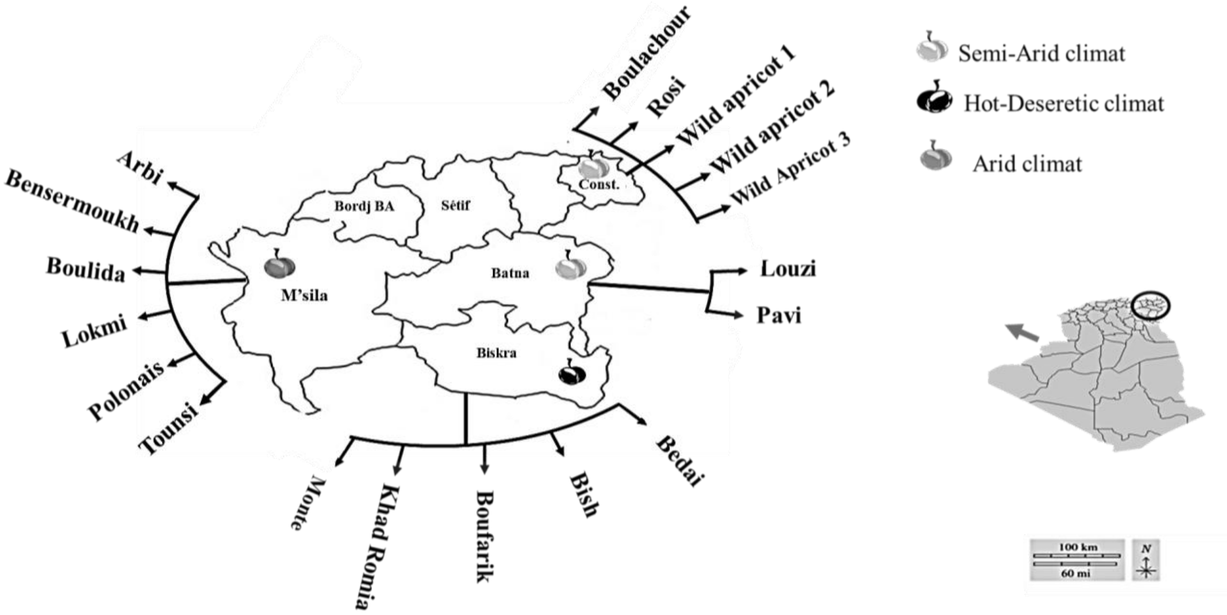

Fig. 1. Position of the cultivars sampled in the different climatic regions of Algeria. Constantine (Const).

Experimental layout

The experiment was conducted during 2021 and 2022, utilizing hourly temperature data obtained from a meteorological website (https://weatherspark.com/). This study represents the first effort in Algeria to evaluate the cold and heat requirements of apricot cultivars by examining the timing of leaf abscission. The onset of dormancy is influenced by both photoperiod and temperature, which vary regionally. Data were recorded in late November and early December, aligning with leaf shedding and branch collection for two cold seasons (27 November 2020 and 19 November 2021) until the conclusion of dormancy. Due to differences in climatic zones, there was a two-week variation in timing between Biskra and other areas. The first year experienced earlier and colder winters compared to the second year, with Batna and Constantine being the coldest regions (Fig. 2).

Three branches, approximately 40 to 60 cm in length and 0.8 to 1.5 cm in diameter, were collected from 10 replicate trees for each cultivar. These branches were randomly sampled once a month from each cultivar. They were then immersed in a water solution within a growth chamber set to a photoperiod of 16 hours of light and 8 hours of darkness, with the water changed twice weekly. After a duration of 5 to 10 days, phenological stage observations began. Dormancy breakthrough was considered complete when 30% of the flower buds had reached the Baggiolini stage B-C (Fig. 3) (Ruiz et al., 2007).

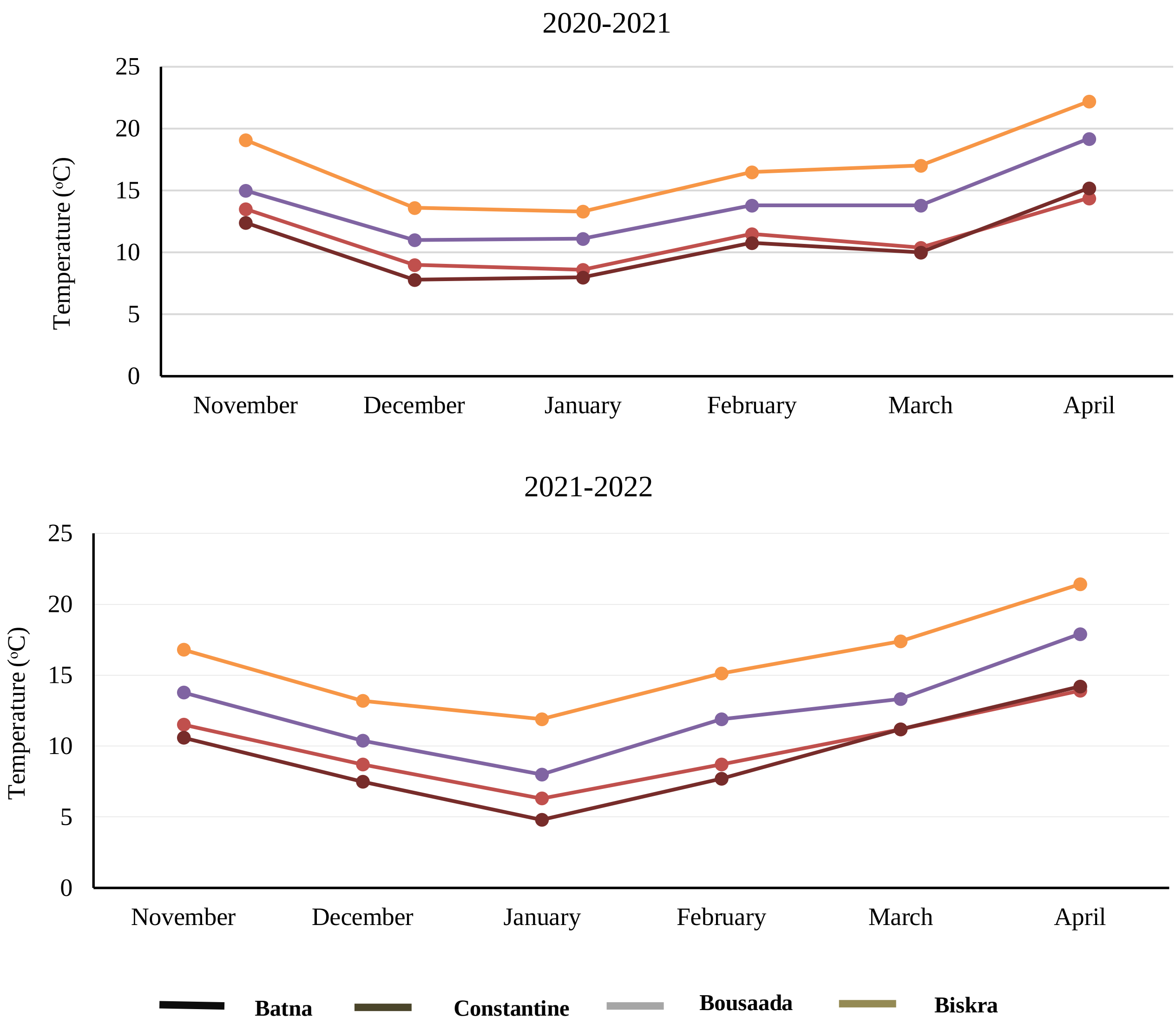

Fig. 2. Mean temperature values of 2020/2021 and 2021-2022 cold seasons in the region.

Determination of chill and heat requirements

Chill requirements were assessed using three universal models: hours below 7 °C to estimate chill hours (CH) (Weinberger, 1950), the Utah model for chill units (CU) (Richardson et al., 1974), and the chill portion (CP) measured by the dynamic model (Fishman et al., 1987a, 1987b). Conversely, the growing degree hours (GDH) model was employed to estimate the heat requirement from the end of dormancy until 50% of flowers had opened (F50) in the experimental orchard. Flowering dates were recorded based on observations of bud flowering, conducted at two-week intervals (Richardson et al., 1974).

Data analysis

The estimation of chill and heat requirements was performed using Excel. Significant differences between groups were assessed with Duncan's multiple range test, and coefficients of variation (CV%) were calculated to evaluate variability. Pearson's correlation coefficients were determined to examine correlations between traits and genotypes. Statistical analyses were conducted using SPSS version 26.0 for Windows.

Fig. 3. Baggiolini stage (B-C). Stage B: bud swelling, Stage C: bud burst.

Results

Chill requirements

Significant differences were observed in the chilling requirements among the studied cultivars. The chilling requirements, estimated by the three models for the 18 apricot cultivars, ranged from 225 to 1152 CH when using the Weinberger model, from 122 to 1525 CU when using the Utha model, and from 26 to 72 CP with the chill portion, indicating a wide range of patterns of chilling accumulation (Table 1). The Utah model revealed negative values for the varieties cultivated in the desert region of Biskra, so the results pertaining to these five varieties were not considered.

The cultivars were classified into three groups based on their chilling requirements (Table 1): low-chill cultivars (Bedai, Boufarik, Monte, KhadRomia, and Bish), moderate-chill cultivars (Tounsi, Boulida, Bensermoukh, Arbi, Polonai, wild apricot varieties 1, 2, and 3, and Lokmi), and high-chill cultivars (Boulachour, Pavi, Rosi, and Louzi). A strong correlation was observed between the flowering date and the end of dormancy date (r = 0.962) (Table 2). Our results revealed a well-distributed pattern of varieties: low-chill cultivars were found in the warm and desert region of Biskra, moderate-chill cultivars were present in the arid region of Bousaâda, and high-chill cultivars were located in the semi-arid regions of Batna and Constantine.

The coefficient of variation (CV%) for the chilling requirements of the 18 evaluated cultivars, including 13 cultivars for the Utah model, varied depending on the method used: 13.10% with the Utah model, 13.81% with the dynamic model, and 21.19% with the Weinberger model. Additionally, the CV% between years showed significant differences, ranging from 2.61% to 35.31% for the Weinberger method, from 5.21% to 18.97% for the Utah model, and from 5.88% to 26.66% for the dynamic model (Table 1). The CV% was a reliable indicator of the homogeneity of the three models across different years and cultivars. A strong, significant, and positive correlation was observed among the three models; however, no correlation was found between the models and the end of dormancy date. In this study, the cultivar Boulida, used as a reference, exhibited average chilling accumulation.

Heat requirements

According to the Richardson model, the heat requirements for flowering varied significantly from year to year, ranging from 1017.7 to 5597 growing degree hours (GDH) (Table 1). Most cultivars showed similar values from year to year, with a CV% ranging from 0.77% to 9.35%, while notable differences were observed in others, with a CV% ranging from 14.83% to 37.62% (see Table 1). The results revealed significant differences in heat requirements for flowering among the cultivars. Notably, the low-chill cultivar Khad Romia had the highest heat requirement (5597 GDH), while the high-chill cultivar Rosi had the lowest heat requirement (1186 GDH). The CV% for the heat requirements across cultivars was 14.17% over several years, indicating model homogeneity.

The categorization based on heat requirements for the 18 cultivars includes those with very low heat requirements, specifically Rosi and Sauvage (3, 2), while cultivars with low heat requirements are Pavi, Bish, Louzi, Sauvage 1, Boulachour, Bensermoukh, Arbi, Tounsi, and Polonais. Cultivars with moderate heat requirements include Boulida, Lokmi, Bedai, Boufarik, and Monte. The cultivar Khad Romia exhibited the highest heat requirements among all the studied cultivars. A significantly positive relationship was found between chilling requirements for breaking dormancy and heat requirements for flowering

(Table 2), with high correlation coefficients observed using the dynamic model (R = -0.641), the Weinberger model (R = -0.666), and the Utah model (R = -0.658). The highest correlation coefficient was obtained with chilling hours (Weinberger model). The relationship between heat requirements and flowering date was not clearly established.

Table 1. The chill requirement is estimated by the three models: chill below 7-degree hours (CH), dynamic model (CP), and Utah model (CU). The heat is estimated by the GDH model. The date of breaking dormancy (BD) and the date of 50% of flowering (FD 50%) were also determined. (A) cultivars with low chill requirements, (B) cultivars with medium chill requirement, (C) cultivars with high chill requirements, (D) Mean, standard deviation (SD) and Coefficient of variation (CV%) of all cultivars. Different lowercase letters in the same column indicate significant differences among cultivars. ANOVA tests were conducted for each variable studied, and differences between groups were determined by Duncan's multiple range test (P < 0.05), The significant differences between the genotypes were indicated by lowercase letters (a, b, c, and d).

(A)							
		Chill Requirement			Heat		
Year	**Cultivar**	**CH**	**CU**	**CP**	**GDH**	**BD**	**FD 50%**
2021	**Bedai**	153		20	3808	12 February 2021	26 February 2021
2022		297		31	3157	04 February 2022	03 March 2022
	Mean	**225[a]**		**26[a]**	**3483[c]**		
	SD	72		6	326		
	CV%	32		21.57	9.35		
2021	**Boufarik**	153		20	3808	05 February 2021	19 February 2021
2022		320		33	3157	19 February 2022	03 March 2022
	Mean	**237[a]**		**27[a]**	**3483[c]**		
	SD	84		7	326		
	CV%	35.31		24.53	9.35		
2021	**Khad Romia**	174		22	6119	19 February 2021	05 March 2021
2022		314		33	5075	11 February 2022	03 March 2022
	Mean	**244[a]**		**28[a]**	**5597[d]**		
	SD	70		6	522		
	CV%	28.69		20	9.33		
2021	**Bish**	176		22	2358	05 March 2021	12 March 2021
2022		341		38	2685	11 March 2022	18 March 2022
	Mean	**259[a]**		**30[a]**	**2522[b]**		
	SD	83		8	164		
	CV%	31.91		26.67	6.48		
2021	**Monte**	153		20	3803	12 February 2021	26 February 2021
2022		314		33	3862	11 February 2022	25 February 2022
	Mean	**234[a]**		**27[a]**	**3833[c]**		
	SD	81		7	30		
	CV%	34.48		24.53	0.77		
(B)							
2021	**Tounsi**	491	631	38	2734	22 January 2021	05 February 2021
2022		649	882	45	3185	28 January 2022	19 February 2022
	Mean	**570[b]**	**757[a]**	**42[b]**	**2960[b]**		
	SD	79	126	4	226		
	CV%	13.86	16.59	8.43	7.62		

2021	**Boulida**	523	669	39	2988	29/02/2021	12 February 2021
2022		690	924	48	3471	04 February 2022	25 February 2022
	Mean	**607[b]**	**797[a]**	**44[b]**	**3230[c]**		
	SD	84	128	5	242		
	CV%	13.77	16.01	10.34	7.48		
2021	**Bensermoukh**	550	698	41	2486	05 February 2021	19 February 2021
2022		746	988	52	3352	11 February 2022	03 March 2022
	Mean	**648[b]**	**843[a]**	**47[b]**	**2919[b]**		
	SD	98	145	6	433		
	CV%	15.12	17.2	11.83	14.83		
2021	**Arbi**	550	698	41	2486	05 February 2021	19 February 2021
2022		746	988	52	3352	11 February 2022	03 March 2022
	Mean	**648[b]**	**843[a]**	**47[b]**	**2919[b]**		
	SD	98	145	6	433		
	CV%	15.12	17.2	11.83	14.83		
2021	**Polonai**	579	711	42	2550	12 February 2021	26 February 2021
2022		819	1044	55	3503	19 February 2022	11 March 2022
	Mean	**699[b]**	**878[a]**	**49[b]**	**3027[b]**		
	SD	120	167	7	477		
	CV%	17.17	18.97	13.4	15.74		
2021	**Lokmi**	690	813	49	2559	26 February 2021	12 March 2021
2022		912	1139	61	4198	03 March 2022	25 March 2022
	Mean	**801[c]**	**976[b]**	**55[b]**	**3379[c]**		
	SD	111	163	6	820		
	CV%	13.86	16.7	10.91	24.26		
2021	**Sauvage 1**	590	914	42	3693	27 January 2021	13 February 2021
2022		1075	1253	59	1674	11 February 2022	25 February 2022
	Mean	**833[c]**	**1084[b]**	**51[b]**	**2684[b]**		
	SD	243	170	9	1010		
	CV%	29.13	15.64	16.83	37.62		
2021	**Sauvage 2**	647	1022.5	49	1690.52	07 February 2021	19 February 2021
2022		1024	1203.5	56	1457.5	07 February 2022	25 February 2022
	Mean	**836[c]**	**1113[b]**	**53[b]**	**1574[a]**		
	SD	189	91	4	117		
	CV%	22.56	8.13	6.67	7.4		
2021	**Sauvage 3**	646	1023.5	48	1574.5	05 February 2021	26 February 2021
2022		1075	1252.5	59	1669.5	11 February 2022	25 February 2022
	Mean	**861[c]**	**1138[b]**	**54[b]**	**1622[a]**		
	SD	215	115	6	48		
	CV%	24.93	10.06	10.28	2.93		
(C)							
2021	**Pavi**	840	1000	56	2891	26 February 2021	19 March 2021
2022		885	1110	63	1876	19 February 2022	11 March 2022
	Mean	**863[c]**	**1055[b]**	**60[c]**	**2384[b]**		

	SD	23	55	4	508		
	CV%	2.61	5.21	5.88	21.29		
2021	**Louzi**	891	1046	59	2330	05 March 2021	26 March 2021
2022		942	1165	67	2747	25 February 2022	18 March 2022
	Mean	**917c**	**1106b**	**63c**	**2539b**		
	SD	26	60	4	209		
	CV%	2.78	5.38	6.35	8.21		
2021	**Rosi**	881	1358	66	1186	13 March 2021	20 March 2021
2022		1423	1692	77	2614	11 March 2022	25 March 2022
	Mean	**1152[c]**	**1525[c]**	**72[c]**	**1900[a]**		
	SD	271	167	6	714		
	CV%	23.52	10.95	7.69	37.58		
2021	**Boulachour**	802	1215	58	2187	27 February 2021	13March2021
2022		1325	1555	72	3282	03 March 2022	25 March 2022
	Mean	**1064[c]**	**1385[c]**	**65[c]**	**2735[b]**		
	SD	262	170	7	548		
	CV%	24.59	12.27	10.77	20.02		
(D)							
All cultivars	Mean	655	1039	47	2918		
	SD	322.38	253.16	15.03	996.05		
	CV%	21.19	13.1	13.81	14.17		
ANOVA	F	4,339	8,629	6,139	3,713	11,948	6,148
	Sig	0,002	0,000	0,000	0,004	0,000	0,000

Table 2. Pearson's correlation was conducted to analyze the relationship between chill accumulation of the three models: chill below 7-degree hours (CH), dynamic model (CP), and Utah model (CU), heat accumulation (GDH), and flowering date (FD 50%), breaking of dormancy date (BD). The results showed that the correlations were significant at the 0.01 level (**) and 0.05 level (*).

	CH	CU	CP	GDH	BD	FD 50%
CH	1					
CU	**0,991****	1				
CP	**0,990****	**0,971****	1			
GDH	**-0,666****	**-0,658****	**-0,641****	1		
BD					1	
FD			**0,489***		**0,962****	1

Flowering date

The results indicated significant variation in the flowering date among cultivars ($P < 0.05$) (Table 1). The flowering period ranged from February 5 to March 26, depending on the year. The earliest cultivar to flower was Tounsi, which flowered between February 5 and February 19, 48 days earlier than Rosi. Bish and Pavi were classified as mid-flowering cultivars, with flowering dates around mid-March. The latest flowering cultivars were Rosi and Louzi, with flowering dates around March 25, potentially making them suitable for frost-prone regions. The cultivar Tounsi was classified as early-flowering but with a medium chilling requirement. The correlation between flowering date and chilling requirement was moderately weak ($r = 0.426$). No correlation was observed between flowering date and heat requirement, indicating a closer relationship between flowering date and chilling requirement compared to heat requirement.

Discussion

Chill requirements

The evaluation of chill requirements using mathematical models has been previously conducted on various Prunus species, including peach, Japanese apricot, almond, and cherry (Alonsoa and Socias i Company, 2009; Kaufmann and Blanke, 2017; Li et al., 2016; Zhang et al., 2023), and specifically for apricot (Legave et al., 2010), across different climates and cultivars. However, comparing results across studies presents challenges due to several factors that must be considered. These factors include the selection of plant material and protocols, criteria for determining dormancy completion, and environmental conditions during the preceding growing season. To enhance the utility of chilling requirement data, it is essential to complement it with information on tree behavior, location, conditions, and the duration over which chilling requirements were assessed (Gao et al., 2012). In the present study, chilling requirements varied among cultivars across different experimental seasons due to variable weather conditions. The onset of dormancy was earlier in the second season (November 19, 2021) compared to the first (November 27, 2020), resulting in an earlier release from dormancy. However, despite the early onset of dormancy, bud burst did not occur earlier, suggesting that heat was a key factor in bud burst following sufficient chilling accumulation.

The observed variation in chilling requirements aligns with findings from other studies involving different species. It has been reported that populations within species often have different cold and heat requirements, primarily due to their original climates (Zhuang et al., 2016). Additionally, a wide range of chill accumulation has been observed in other studies, with cold requirements varying from 274 CU for 'Palsteyn' to 1450-1600 CU for 'Orangered' among 68 apricot cultivars from Iran, Italy, Serbia, South Africa, Spain, and the United States (Fadón et al., 2020b). These differences are attributed to varied environmental conditions in the studied regions. According to our findings, the Utah model (CU) proved unsuitable for the evaluated varieties in the Biskra region, characterized by a hot desert climate (Table 1). This may be due to the fact that the Utah model was initially developed in a cooler climate (Dirlewanger et al., 2004). Significant differences were observed between the two study years for each cultivar, a finding also noted by Campoy et al. (2012).

The significant correlation found between flowering date and dormancy break indicates that cultivars with low chilling requirements tend to flower earlier, while those with high chilling requirements flower later. Dormancy generally ends when conditions become more favorable for growth, ultimately promoting flowering. This trend has been reported in apricot cultivars (Zhuang et al., 2016) and other Prunus species (Fadón et al., 2020b). The clear and distinct distribution of the studied cultivars across Eastern Algeria does not necessarily explain their geographical origin. Other studies have identified cultivars with different chilling requirements in the same regions, suggesting that a cultivar's chilling accumulation is not necessarily linked to its place of origin (Fadón et al., 2020b). Therefore, there is a need for breeding programs focusing on varieties with low chilling requirements, which are better suited to warmer climates and more adaptable to climate change (Zhebentyayeva et al., 2012). The five identified varieties with reduced chilling requirements in our study—Khad Romia, Monte, Bish, Bedai, and Boufarik—are potential candidates for future apricot breeding programs. The comparison of mathematical models for calculating chilling requirements demonstrated that the dynamic model was the most effective for estimating apricot chilling requirements across different climates in Algeria, surpassing the other two models. These results were consistent with previous studies, where CU and CP provided homogeneous estimations among cultivars (Ruiz et al., 2007).

The high positive correlation among the three models indicated their similarity in estimating chilling requirements. Similar results have been reported in multiple studies estimating chilling for apricot and peach (Alburquerque et al., 2008; Guo et al., 2015; Maulión et al., 2014; Razavi et al., 2011; Rodríguez et al., 2021). No correlation was found between the three models and the dormancy release date. Apricot trees may exhibit unpredictable behavior from year to year due to significant variations in their growth patterns. Furthermore, a close correlation was observed between dormancy release and chilling requirements, especially under certain climatic conditions for species such as apricot (Campoy et al., 2012), apple and almond (El Yaacoubi et al., 2016), sweet cherry (Kaufmann and Blanke, 2017), and pomegranate (Nasrabadi et al., 2020), which contrasts with the results of our study.

The Bulida variety exhibited lower chilling requirements compared to other studies conducted in different climates, but it was still classified as a cultivar with medium chilling requirements (Campoy et al., 2012). Fadón et al. (2020b) reported similar significant results for the Canino, Orangered, and Palsteyn cultivars, with higher values in Spain (806, 1172, and 631 CU) compared to South Africa (304, 957, and 274 CU). This divergence may be due to synonymy or homonymy or the cultivar's different behavior in various climates. This study suggests that apricot cultivation is significantly influenced by climatic conditions, particularly chilling accumulation, in various growing areas. Understanding and managing these factors are essential for successful apricot production and future breeding programs.

Heat requirements

Significant differences in heat requirements have been documented by several researchers on various fruit tree species, including almonds (Egea et al., 2003), apricots (Campoy et al., 2012), sweet cherry (Alburquerque et al., 2008), and pistachios (Benmoussa, 2018). This phenomenon, where cultivars with low chilling requirements exhibit higher heat requirements, has also been observed in peach (Pantelidis and Drogoudi, 2023). This may be due to the fact that these cultivars end their dormancy during a particularly cold period of the year, when growing degree hour (GDH) accumulation is likely less effective compared to later dates with higher temperatures (Campoy et al., 2011a). Genetic improvement programs targeting characteristics associated with high heat requirements are beneficial in regions prone to early frosts, as they help in preventing frost damage. Thus, varieties with high heat requirements are potential candidates for breeding programs.

The correlation between chilling and heat requirements has also been observed in ornamental peach trees in previous research (Guo et al., 2014), indicating that heat requirements are influenced by the amount of cold exposure. Prolonged cold exposure generally leads to a decrease in heat requirements. However, these findings contradict those of other studies where no correlation was found between these parameters in apricot cultivars (Guerriero et al., 2002) and in almonds and nectarines (Egea et al., 2003; Linsley-Noakes and Allan, 1994). These contradictory results may be attributed to variations in climatic conditions, particularly temperature. In our study, heat requirements and flowering date showed no correlation, suggesting that flowering date did not necessarily correspond to heat requirements. Variations in flowering dates among varieties were primarily influenced by chilling requirements, which contradicts findings from other studies (Campoy et al., 2011a).

Flowering date

A significant correlation was observed between the dynamic model and the end dates of dormancy, indicating that chilling requirements had a greater impact on flowering dates than heat requirements. Similar findings have been reported in other studies (Egea et al., 2020). The variability in flowering dates among early cultivars, such as Tounsi, highlights the importance of considering chilling requirements for accurate classification. Climatic factors, the growing environment, and shading from surrounding trees in the orchard may contribute to the observed differences in flowering dates. The relationship between flowering dates and chilling requirements has been documented in other fruit studies (Fadón et al., 2020b; Guo et al., 2014), including apricot, almond, pistachio, and sweet cherry cultivars. Our results support the notion that flowering dates are influenced not only by heat and chilling requirements but also by other factors.

This study offers valuable insights into the chilling and heat requirements of different apricot cultivars, which can be used to assess how crops will adapt to current and future climatic conditions in specific areas. This information is crucial for breeding programs aiming to identify suitable parental plants for developing improved cultivars with earlier flowering dates (characterized by low chilling requirements and high heat requirements) and cultivars capable of thriving under future climate conditions. The 18 examined cultivars were categorized into three groups based on their chilling requirements, revealing notable variations in both chilling and heat requirements as well as flowering dates. To summarize the groups and their characteristics: low-chilling and high-heat-requirement cultivars were Bedai, Boufarik, Monte, and Khad Romia. Moderate-chilling-requirement cultivars were Tounsi, Boulida, Bensermoukh, Arbi, Polonai, Wild Apricot (1, 2, 3), and Lokmi. High-chilling-requirement with low-heat-requirement cultivars were Boulachour, Pavi, and Louzi.

Acknowledgments

The authors would like to express their gratitude to the Algerian Ministry of Higher Education and Scientific Research and the General Directorate of Scientific Research and Technological Development, Algeria, for their support. This work was funded by the FNRSDT/DGRSDT as part of the PRIMA framework.

Conflict of Interest

The authors indicate no conflict of interest in this work.

References

Alburquerque N, García-Montiel F, Carrillo A, Burgos L. 2008. Chilling and heat requirements of sweet cherry cultivars and the relationship between altitude and the probability of satisfying the chill requirements. Environmental and Experimental Botany 64 (2), 162–170.

Ali A, Franzoni G, Petrini A, Santoro P, Mori J, Ferrante A, Cocetta G. 2023a. Investigating physiological responses of Wild Rocket subjected to artificial Ultraviolet B irradiation. Scientia Horticulturae 322, 112415.

Ali A, Hussain T, Tantashutikun N, Hussain N, Cocetta G. 2023b. Application of Smart Techniques, Internet of Things and Data Mining for Application of Smart Techniques, Internet of Things and Data Mining for Resource Use Efficient and Sustainable Crop Production. Agriculture 13 (2), 397.

Ali A, Soonsuwon W, Nualsri C. 2019. Induced mutagenesis for creating variability in Thailand's upland Rice (cv. Dawk Pa-yawm and Dawk Kha 50) using Ethyl Methane Sulphonate (EMS). Sarhad Journal of Agriculture 35 (1), 293-301.

Alonsoa JM, Socias I Company R. 2009. Chill and heat requirements for blooming of the CITA almond cultivars. Acta Horticulturae 814, 215–220.

Andreini L, De Cortázar-Atauri IG, Chuine I, Viti R, Bartolini S, Ruiz D, Campoy JA, Legave JM, Audergon JM, Bertuzzi P. 2014. Understanding dormancy release in apricot flower buds (Prunus armeniaca L.) using several process-based phenological models. Agricultural and Forest Meteorology 184, 210–219.

Bassi D, Viti R, Bartolini S. 2006. Recent advances on environmental and physiological challenges in apricot growing. Acta Horticulturae 717, 23–31.

Benmoussa H. 2018. Estimation des besoins en froid et en chaleur des variétés d'amandier (Prunus dulcis Mill.) et de pistachier (Pistacia vera L.) en Tunisie. PhD thesis, University of Carthage, Tunisia.

Bourguiba H, Audergon JM, Krichen L, Trifi-Farah N, Mamouni A, Trabelsi S, D'Onofrio C, Asma BM, Santoni S, Khadari B. 2012. Loss of genetic diversity as a signature of apricot domestication and diffusion into the Mediterranean Basin. BMC Plant Biology 12, 1–17.

Campoy JA, Ruiz D, Allderman L, Cook N, Egea J. 2012. The fulfilment of chilling requirements and the adaptation of apricot (Prunus armeniaca L.) in warm winter climates: an approach in Murcia (Spain) and the Western Cape (South Africa). European Journal of Agronomy 37 (1), 43–55.

Campoy JA, Ruiz D, Cook N, Allderman L, Egea J. 2011a. High temperatures and time to budbreak in low chill apricot "Palsteyn". Towards a better understanding of chill and heat requirements fulfilment. Scientia Horticulturae 129 (4), 649–655.

Campoy JA, Ruiz D, Egea J. 2011b. Dormancy in temperate fruit trees in a global warming context: A review. Scientia Horticulturae 130 (2), 357–372.

Dirlewanger E, Claverie J, Iezzoni AF, Ana W. 2009. Sweet and sour cherries: linkage maps, QTL detection and marker assisted selection (1st ed.). New York, Springer.

Dirlewanger E, Graziano E, Joobeur T, Garriga-Calderé F, Cosson P, Howad W, Arús P. 2004. Comparative mapping and marker-assisted selection in Rosaceae fruit crops. Proceedings of the national academy of sciences of the United States of America 101(26), 9891–9896.

Egea J, López-Alcolea J, Campoy JA, Egea JA, Ruiz D. 2020. Global warming and breaking dormancy in apricot: Some interesting related aspects. In XVII International Symposium on Apricot Breeding and Culture 1290, 213-216.

Egea J, Ortega E, Martínez-Gómez P, Dicenta F. 2003. Chilling and heat requirements of almond cultivars for flowering. Environmental and Experimental Botany 50 (1), 79–85.

El Yaacoubi A, Malagi G, Oukabli A, Citadin I, Hafidi M, Bonhomme M, Legave J-M. 2016. Differentiated dynamics of bud dormancy and growth in temperate fruit trees relating to bud phenology adaptation, the case of apple and almond trees. International journal of biometeorology 60, 1695–1710.

Fadón E, Fernandez E, Behn H, Luedeling E. 2020a. A conceptual framework for winter dormancy in deciduous trees. Agronomy 10 (2), 241.

Fadón E, Herrera S, Guerrero BI, Guerra ME, Rodrigo J, Engracia Guerra M, Rodrigo J. 2020b. Chilling and heat requirements of temperate stone fruit trees (Prunus sp.). Agronomy 10 (3), 409.

Fishman S, Erez A, Couvillon GA. 1987a. The temperature dependence of dormancy breaking in plants: Computer simulation of processes studied under controlled temperatures. Journal of Theoretical Biology 126, 309–321.

Fishman S, Erez A, Couvillon GA. 1987b. The Temperature Dependence of Dormancy Breaking in Plants: Mathematical Analysis of a Two-Step Model Involving a Cooperative Transition. Journal of Theoretical Biology 124, 473–483.

Gao Z, Zhuang W, Wang L, Shao J, Luo X, Cai B, Zhang Z. 2012. Evaluation of chilling and heat requirements in Japanese apricot with three models. HortScience 47 (12), 1826–1831.

Guerriero R, Gentili M, Monteleone P, Viti R. 2002. La valutazione della dormienza nell'albicocco: tre metodi a confronto. Rivista di frutticoltura e di ortofloricoltura 64 (3), 73–78

Guo L, Dai J, Ranjitkar S, Yu H, Xu J, Luedeling E. 2014.

Chilling and heat requirements for flowering in temperate fruit trees. International Journal of Biometeorology 58, 1195–1206.

Guo L, Xu J, Dai J, Cheng J, Luedeling E. 2015. Statistical identification of chilling and heat requirements for apricot flower buds in Beijing, China. Scientia Horticulturae 195, 138–144.

Kaufmann H, Blanke M. 2017. Performance of three numerical models to assess winter chill for fruit trees—a case study using cherry as model crop in Germany. Regional Environmental Change 17, 715–723.

Legave JM, Baculat B, Brisson N. 2010. Assessment of chilling requirements of apricot floral buds: Comparison of three contrasting chilling models under mediterranean conditions. Acta Horticulturae 872, 41–50.

Li Y, Fang WC, Zhu GR, Cao K, Chen CW, Wang XW, Wang LR. 2016. Accumulated chilling hours during endodormancy impact blooming and fruit shape development in peach (Prunus persica L.). Journal of Integrative Agriculture 15 (6), 1267–1274.

Linsley-Noakes GC, Allan P. 1994. Comparison of two models for the prediction of rest completion in peaches. Scientia Horticulturae 59 (2), 107–113.

Mahmoud TSH. M. 2016. Adaptability of three newly introduced apricot (Prunus armeniaca L.) cultivars to Egyptian conditions. Future of Food: Journal on Food, Agriculture and Society 4, 13-23

Maulión E, Valentini GH, Kovalevski L, Prunello M, Monti LL, Daorden ME, Quaglino M, Cervigni GDL. 2014. Comparison of methods for estimation of chilling and heat requirements of nectarine and peach genotypes for flowering. Scientia Horticulturae 177, 112–117.

Muluneh MG. 2021. Impact of climate change on biodiversity and food security: a global perspective—a review article. Agriculture & Food Security 10 (1), 1–25.

Nasrabadi M, Ramezanian A, Eshghi S, Sarkhosh A. 2020. Chilling and heat requirement of pomegranate (Punica granatum L.) trees grown under sustained deficit irrigation. Scientia Horticulturae 263, 109117.

Nishitani C, Hirai N, Komori S, Wada M, Okada K, Osakabe K, Yamamoto T, Osakabe Y. 2016. Efficient Genome Editing in Apple Using a CRISPR/Cas9 system. Scientific Reports 6 (1), 31481

Pantelidis G, Drogoudi P. 2023. Exploitation of genotypic variation in chilling and heat requirements for flowering in Prunus armeniaca and Prunus persica (L.) Batsch cultivars. Scientia Horticulturae 321, 112287.

Pio R, Bittencourt F, Souza M De, Kalcsits L, Bisi RB, Farias H. 2019. Acta Scientiarum Advances in the production of temperate fruits in the tropics. Acta Scientiarum. Agronomy 41, e39549.

Ramírez F, Kallarackal J. 2015. Responses of fruit trees to global climate change — Basics and applications (1st ed.). London, Springer.

Razavi F, Hajilou J, Tabatabaei SJ, Dadpour MR. 2011. Comparison of chilling and heat requirement in some peach and apricot cultivars. Research in Plant Biology 1, 40–47

Richardson EA, EA R, SD S, DR W. 1974. A model for estimating the completion of rest for" Redhaven" and" Elberta" peach trees. Horticultural Science 9, 311-312.

Rodríguez A, Pérez-López D, Centeno A, Ruiz-ramos M. 2021. Viability of temperate fruit tree varieties in Spain under climate change according to chilling accumulation. Agricultural Systems 186, 102961.

Ruiz D, Campoy JA, Egea J. 2007. Chilling and heat requirements of apricot cultivars for flowering. Environmental and Experimental Botany 61(3), 254–263.

Ruml M, Milatović D, Đurović D, Zec G, Jokić M, Radović M. 2018. Chilling and heat requirements for flowering in apricot cultivars. Acta Horticulturae 1214, 15–18.

Sahnoune F, Belhamel M, Zelmat M, Kerbachi R. 2013. Climate change in Algeria: Vulnerability and strategy of mitigation and adaptation. Energy Procedia 36, 1286–1294.

Salama AM, Ezzat A, El-Ramady H, Alam-Eldein SM, Okba S, Elmenofy HM, Hassan IF, Illés A, Holb IJ. 2021. Temperate fruit trees under climate change: Challenges for dormancy and chilling requirements in warm winter regions. Horticulturae 7 (4), 86.

Shivanna KR. 2022. Climate change and its impact on biodiversity and human welfare. Proceedings of the Indian National Science Academy 88 (2), 160–171.

Venturi M, Giovannini A, Gutiérrez-Gordillo S, Manfrini L, Corelli-Grappadelli L, Morandi B. 2022. Apricot water relation and fruit growth under progressive water stress conditions. XXXI International Horticultural Congress (IHC2022): International Symposium on Water: A Worldwide Challenge for Horticulture 1373, 73–80.

Wang Y, Sun H, Zhang J, Jiang F, Yang L, Zhang M. 2022. The Apricot Genome — Basics and applications (1st ed.). Cham, Springer.

Weinberger JH. 1950. Chilling requirements of peach varieties. Proceedings. American Society for Horticultural Science 56, 122–128.

Zhang Y, Ma K, Li Q. 2023. Research on Chilling requirement and physiological mechanism of *Prunus mume*. Horticulturae 9 (5), 603.

Zhebentyayeva T, Ledbetter C, Burgos L, Llácer G. 2012. "Apricot," in Fruit Breeding, Ed. M. Badenes and D. Byrne, Boston, MA: Springer, 415–458.

Zhuang W, Cai B, Gao Z, Zhang Z. 2016. Determination of chilling and heat requirements of 69 Japanese apricot cultivars. European Journal of Agronomy 74, 68–74.