Base Temperature Comparisons for Leafing Date, Pistillate Flower Receptivity, and Pollen Shedding in Persian Walnut

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Abstract

Leafing dates and the male and female bloom periods in Persian walnut (Juglans regia L.) vary with cultivars and years. Changes in phenological phases and the process of passing through the phenological stages could be explained by the growing degree days (GDD) if the minimum base temperature (Tb) were determined. In this study, the long-term phenological data of some walnut cultivars derived and/or grown in Hungary and Iran were used to determine the Tb values for leafing date (LD), pistillate flower receptivity start (PRS), pistillate flower receptivity end (PRE), and start and end of the pollen shedding period (PSS and PSE, respectively). The GDD were calculated (with 0.1 °C precision) for the LD and PSS with respect to the earliest cultivar as well as for PRS compared to LD and PRE. Furthermore, the GDD were reckoned for PSE based on PRS and PSS of the same cultivar in each year. The analysis of the data revealed that for the LD, PRS, and PRE, the Tb 5.5 with the highest correlation was shown to be the most appropriate. For the PSS and PSE, the best correlation was observed at Tb 0 in both countries. The strongest coefficients were observed (0.72 for Iranian and 0.8 for Hungarian conditions) between GDD with Tb of 5.5 °C for PRS and LD. The less correlation was observed between LD and PSS (0.5 for Iranian and 0.57 for Hungarian conditions). The correlation coefficients between GDD and leafing date were the same (0.52) in both countries. Cultivars involved in the trial required more GDD in Iran than in Hungary.

Keywords Cultivars · Hungary · Iran · Juglans regia L · Phenology

Introduction

Fruit production faces major challenges to ensure annual production levels. Although site conditions seem to be more or less stable, temperature and precipitation show great variability, which are likely the initiating factor of annual effects on phenological phases (Hereford et al. 2006; Zaitchik et al. 2007). The warming trend of climate change greatly affects the phenology of cultivated plants. Perennial fruit tree species and their phenological phases are the best markers of the effects of climate change, due to their longevity (Blanke and Kunz 2014; Menzel et al. 2006).

Temperature has a crucial role in bud development during the dormant stages to budburst (Hänninen 2016). For chilling there are some models to calculate the leafing time for many woody tree species, including nut tree species (Luedeling et al. 2009a; 2009b). However, for modeling of the flowering period, no model is yet known (Dennis 2003; Luedeling et al. 2009c).

Temperature is the main factor for raising the speed of phenology, as higher temperatures lead to early switching to the next ontogenetic stage (Badeck et al. 2004). Strong correlations were found between the budbreak dates and the mean air temperature in several studies (Bergant et al. 2001; Chmielewski et al. 2004; Chmielewski and Rötzer 2001; Črepinšek et al. 2006; Menzel 2003; Menzel et al. 2006). In other research (Črepinšek et al. 2009; Kramer et al. 2000; Menzel et al. 2006), it was reported that spring phenophases could be advanced by 2 to 4.6 days per each
Table 1  Base temperatures (Tb) of some phenological stages for fruit tree species

| Fruit tree species/cultivar | Tb for sprouting (°C) | Tb of start of flowering\(a\) (°C) | GDD from the dormant period until bud swell | References |
|----------------------------|------------------------|-----------------------------------|---------------------------------------------|------------|
| Some peach cultivars       | 8                      | 10                                | –                                           | Souza et al. (2011) |
| ‘Tropic Beauty’ peach      | 2.2                    | –                                 | 90.1 ± 20.6                                 | Rafael and Biasi (2016) |
| ‘Eragil’ peach             | 6.3                    | –                                 | 105.9 ± 19.5                                | Rafael and Biasi (2016) |
| ‘Sunblaze’ nectarine       | 8                      | 10                                | –                                           | Souza et al. (2011) |
| ‘Niagara Rosada’ grape     | 10                     | 10                                | –                                           | Ribeiro et al. (2009) |
| ‘Cabernet Sauvignon’ grape | 10                     | 10                                | 170.0 ± 41.0                                | Moura et al. (2009) |
| ‘Cabernet Sauvignon’ grape | 4.3                    | –                                 | 443.8 ± 12.7                                | Ribeiro et al. (2009) |
| ‘BRS Vitoria’ seedless table grape | 10              | 10                                | –                                           | Borges et al. (2017) |
| ‘Chardonnay’ grape         | 2.1                    | –                                 | 447.7 ± 7.0                                 | Rafael and Biasi (2016) |
| ‘Hayward’ kiwifruit        | 10                     | 10                                | –                                           | Kerr et al. (1981; Salinger and Kenny 1995) |
| ‘Hayward’ kiwifruit        | 8.2                    | –                                 | 315.5 ± 9.9                                 | Rafael and Biasi (2016) |
| ‘Golden King’ kiwifruit    | 4.3                    | –                                 | 283.0 ± 19.9                                | Rafael and Biasi (2016) |
| ‘Gulf Blaze’ plum          | 2.2                    | –                                 | 131.9 ± 12.6                                | Rafael and Biasi (2016) |
| ‘Letícia’ plum             | 6.2                    | –                                 | 137.2 ± 27.4                                | Rafael and Biasi (2016) |
| ‘Smith’ pear               | 4.4                    | –                                 | 58.7 ± 17.1                                 | Rafael and Biasi (2016) |
| ‘Packhams’ pear            | 8.2                    | –                                 | 72.3 ± 8.6                                  | Rafael and Biasi (2016) |

\(GDD\) growing degree days
\(a\)From the swollen bud to the open flower

Celsius degree of heat accumulation in the month before onset.

Previous studies in pome fruits, stone fruits, and berries showed that the minimum base temperature varied not only by fruit tree species but also by cultivars among species. Studies for determining the base temperatures for growth, sprouting, or leafing of peach and nectarine showed that, for *Prunus persica* sprouting, the base temperature (Tb) varied from 2.2 °C in ‘Tropic Beauty’ to 8 °C in ‘Sunblaze’ nectarine cultivar (Rafael and Biasi 2016; Souza et al. 2011). Table 1 contains data for the Tb of phenological stages for several fruit tree species.

In walnut, the leafing of ‘Franquette’ showed a correlation with the April mean temperature value \((r = −0.84)\), which meant that the high air mean temperature would be followed by earlier budbreak. The correlation showed a slight increase from January until April (Črepinšek et al. 2009). In another study (Hassankhah et al. 2017), the same results between air mean temperature and growing degree hour demands of terminal buds and catkins were obtained. In hazelnut (Taghavi et al. 2017), strong correlations between some phenological stages of terminal leaf buds, catkins, female flower buds, and daily mean temperatures were observed. An increase of mean temperature from January until April of about 0.9 °C correlated with 7 days of advance in budbreak of ‘Franquette’ and 3 days in Geisenheim selection G-139 (Črepinšek et al. 2009). Similar results were found in apple, sweet cherry, pear, and locust trees (Bergant et al. 2001; Chmielewski and Rötzer 2001; Walkovszky 1998).

As the base temperature has a key role in predicting the phenological phases of walnut cultivars, the study was conducted to determine the Tb for leafing date (LD), period of pistillate flower receptivity (start of pistillate flower receptivity PRS; end of pistillate flower receptivity PRE), and the start (PSS) and end (PSE) of the pollen shedding period.

**Material and Methods**

**Description of the Cultivars**

Two cultivars from the National Agricultural Research and Innovation Centre breeding program were involved in this trial. The early-leafing ‘Milotai 10,’ selected from the local population, is the most cultivated in Hungary and in other countries such as Slovakia, Georgia, and Bulgaria due to its excellent fruit characteristics (large fruit size, light shell and kernel colour, smooth shell surface, excellent flavor, good kernel rate) (Bujdosó et al. 2010). The other variety, derived from the breeding program of the Research Institute, is the novel-bred, late-leafing ‘Milotai kései,’ from a cross of ‘Milotai 10’ and ‘Pedro.’ This variety also has large fruit size and excellent fruit characteristics (Bujdosó et al. 2010).
Table 2  Meteorological parameters during 2010–2019 in Hungary and Iran

| Parameter                        | Hungary (°C) | Iran (°C) |
|----------------------------------|--------------|-----------|
| Average annual temperature       | 11.5         | 15.8      |
| Average temperature of growing seasona | 16.7         | 21.5      |
| Average monthly temperature      |              |           |
| January                          | –0.2         | 2.6       |
| February                         | 1.6          | 5.0       |
| March                            | 6.5          | 10.4      |
| April                            | 12.3°        | 15.4      |
| May                              | 16.4         | 20.6      |
| Average minimum temperature      |              |           |
| January                          | –3.6         | –9.1      |
| February                         | –2.7         | –7.4      |
| March                            | 0.5          | –2.8      |
| April                            | 4.7          | 1.4       |
| May                              | 9.5          | 7.5       |
| Average maximum temperature      |              |           |
| January                          | 3.5          | 14.0      |
| February                         | 6.1          | 16.3      |
| March                            | 13.8         | 22.4      |
| April                            | 20.3         | 28.3      |
| May                              | 24.1         | 33.4      |

*March to September

2010). The U.S.-bred ‘Chandler’ was included in the trial as well. In Iran, ‘Jamal,’ an early-leafing cultivar released by the Temperate Fruits Research Center of the Horticultural Sciences Research Institute,1 with a terminal bearing habit, large nut size, and excellent nut and kernel characteristics (Hassani et al. 2012, 2020a, b), together with the French late-leafing pollinator cultivar ‘Ronde de Montignac’ (RDM) and the U.S. cultivar ‘Chandler’ were used in the trial.

Description of the Fruit Site Conditions

The selected trees were planted in 1994 in Karaj, Iran (35° 51’ 21.3768” N and 50° 57’ 42.3000” E.), and in 1990 in Elvira major, Hungary (47° 29’ 52.4868” N and 19° 2’ 24.8496” E). All observed trees were grafted on *Juglans regia* L. seedling rootstocks. The experimental orchards were established with three or four grafted trees per plot of the cultivars in a 10 m × 10 m and 7 m × 7 m planting distance, respectively. Meteorological parameters are indicated in Table 2.

Collected Phenological Data

All the phenological stages were recorded as indicated in the CTIFL scheme (Internet 1 2016, Internet 2 2012). The corresponding stages, when the data were collected, were the leafing-time stage, Cf; the start of pistillate flower receptivity, the Ff2 stage; the end of pistillate flower receptivity, the Ff3 stage; the start of pollen shedding, the Em stage; and the end of pollen shedding, the Hm stage. Thus, the start and end of the pollen shedding period were recorded when the catkins started to shed the pollen up to the time they dried and dropped off from the trees. The start and end of the pistillate receptivity period were considered to be when the stigmas in the earliest pistillate flowers became receptive up to the time the last flowers passed though the receptive stages and turned brown. The data were recorded in 2–3-day intervals, usually in the morning. The data were collected in Hungary from 2010 to 2019 and in Iran from 2006 to 2008 and from 2011 to 2019. The average calendar day of the phenological data was put into the model with its related growing degree days (GDD) from 0 to 9 °C at 0.1 °C intervals to find the best correlation.

To estimate the leafing-out time and/or blossom or other phenological phases of the grown plant species, GDD are best to use because there is a linear and direct proportional relationship between the temperature above the threshold and the rate of development of different plant organs (Gallagher 1979; Baker et al. 1986; Sayed 1995). In accordance with several research studies, the early spring stages showed strong correlation with the temperature data, but the yield estimation was challenging due to some errors in the model (Stinner et al. 1974; Ritchie and NeSmith 1991). Therefore, the GDD are an added value to the variety description (McMaster and Smika 1988). Some new methods have been developed to decrease the errors in the models (Haggard et al. 2010; Kawakita et al. 2020; Zhou and Wang 2018).

Results and Discussion

The average leafing date, start and end of pollen shedding, and the start and end of the pistillate receptivity period for walnut cultivars in different years are shown in Table 3. Table 4 shows the phenological data used for the varieties.

The highest coefficient between leafing date and shoot growth was at a base temperature of 5.5 °C (GDD₅₅) in both countries. The coefficient of determination was a bit stronger in Iran (r² = 0.53) than in Hungary (r² = 0.52) (Figs. 1 and 2).

On GDD₅₅ ‘Milotai kései’ needed 99.3 °C more heat accumulation than early-leafing ‘Milotai 10.’ For ‘Chandler’ in Hungarian conditions, the heat accumulation was 59.1 °C, while in Iran, it required 92.1 °C more heat ac-
### Table 3: Average of leafing date (month/day), start of pollen shedding, start of pistillate receptivity, end of pollen shedding, and end of pistillate receptivity in different years in Hungary and Iran (± standard deviation)

| Country   | Year | Leafing date | Start of pollen shedding | Start of pistillate receptivity | End of pollen shedding | End of pistillate receptivity |
|-----------|------|--------------|--------------------------|---------------------------------|------------------------|------------------------------|
| Hungary   | 2010 | 4/22 ± 1.30  | 4/28 ± 1.42              | 5/3 ± 1.40                      | 5/3 ± 1.32             | 5/9 ± 1.55                   |
|           | 2011 | 4/19 ± 1.61  | 4/26 ± 1.16              | 4/25 ± 1.41                      | 5/7 ± 1.04             | 5/5 ± 1.12                   |
|           | 2012 | 4/19 ± 1.91  | 4/29 ± 0.83              | 4/23 ± 1.23                      | 5/10 ± 1.15            | 5/11 ± 1.30                  |
|           | 2013 | 4/23 ± 0.92  | 4/26 ± 1.40              | 4/23 ± 1.23                      | 5/3 ± 1.07             | 5/1 ± 0.88                   |
|           | 2014 | 4/9 ± 1.58   | 4/19 ± 1.28              | 4/18 ± 2.04                      | 5/5 ± 0.00             | 4/30 ± 1.68                  |
|           | 2015 | 4/26 ± 1.26  | 4/29 ± 0.44              | 5/2 ± 1.83                       | 5/12 ± 0.62            | 5/12 ± 1.64                  |
|           | 2016 | 4/14 ± 1.49  | 4/27 ± 1.42              | 4/28 ± 1.87                      | 5/4 ± 1.31             | 5/5 ± 1.91                   |
|           | 2017 | 4/15 ± 1.96  | 4/25 ± 1.76              | 5/3 ± 2.41                       | 5/5 ± 1.24             | 5/13 ± 2.12                  |
|           | 2018 | 4/17 ± 1.33  | 4/24 ± 1.08              | 4/25 ± 1.43                      | 4/29 ± 0.92            | 5/1 ± 1.40                   |
|           | 2019 | 4/18 ± 1.55  | 4/24 ± 0.44              | 4/27 ± 2.16                      | 5/4 ± 0.62             | 5/5 ± 1.65                   |
| Hungary   | total| 4/18 ± 0.51  | 4/26 ± 0.41              | 4/28 ± 0.57                      | 5/5 ± 0.39             | 5/6 ± 0.52                   |
| Iran      | 2006 | 4/11 ± 1.76  | 4/14 ± 1.82              | 4/21 ± 1.44                      | 4/23 ± 1.90            | 4/29 ± 1.50                  |
|           | 2007 | 4/17 ± 1.53  | 4/22 ± 1.75              | 4/28 ± 1.11                      | 4/30 ± 1.81            | 5/4 ± 1.18                   |
|           | 2008 | 4/4 ± 1.55   | 4/4 ± 1.55               | 4/12 ± 1.93                      | 4/11 ± 1.66            | 4/20 ± 2.00                  |
|           | 2011 | 4/12 ± 1.50  | –                         | –                                | –                      | –                            |
|           | 2012 | 4/17 ± 1.69  | 4/19 –                   | –                                | –                      | –                            |
|           | 2013 | 4/5 ± 2.18   | 4/3 ± 1.97               | 4/13 ± 1.88                      | 4/8 ± 2.10             | 4/20 ± 1.92                  |
|           | 2014 | 4/12 ± 2.22  | 4/17 –                   | 4/25 ± 1.57                      | 4/24 –                 | 5/4 ± 1.85                   |
|           | 2015 | 4/5 ± 1.62   | 4/14 ± 1.88              | 4/17 ± 1.32                      | 4/19 ± 1.89            | 4/26 ± 1.13                  |
|           | 2016 | 4/4 ± 2.42   | 4/14 ± 2.23              | 4/18 ± 2.20                      | 4/20 ± 2.32            | 4/25 ± 2.19                  |
|           | 2017 | 4/11 ± 1.58  | 4/20 ± 1.90              | 4/22 ± 1.45                      | 4/29 ± 1.95            | 4/29 ± 1.38                  |
|           | 2018 | 3/29 ± 2.04  | 4/9 ± 2.29               | 4/17 ± 2.07                      | 4/18 ± 2.28            | 4/25 ± 2.10                  |
|           | 2019 | 4/14 ± 1.93  | 4/23 ± 2.02              | 4/27 ± 1.53                      | 5/1 ± 2.00             | 5/4 ± 1.52                   |
| Iran      | total| 4/9 ± 0.54   | 4/14 ± 0.63              | 4/20 ± 0.56                      | 4/21 ± 0.65            | 4/27 ± 0.56                  |
| Grand total|       | 4/13 ± 0.40  | 4/20 ± 0.42              | 4/24 ± 0.42                      | 4/28 ± 0.44            | 5/2 ± 0.40                   |

### Table 4: Average of leafing date (month/day), start and end of pollen shedding, and start and end of pistillate receptivity period in different cultivars in Hungary and Iran (± standard deviation)

| Country   | Cultivar     | Leafing date | Pollen shedding start | Pollen shedding end | Pistillate receptivity start | Pistillate receptivity end |
|-----------|--------------|--------------|-----------------------|---------------------|-----------------------------|---------------------------|
| Hungary   | ‘ChandlerH’  | 4/19 ± 0.79  | 4/22 ± 0.68           | 4/29 ± 0.82         | 5/7 ± 0.78                  |
|           | ‘Milotai 10’ | 4/11 ± 0.80  | 4/27 ± 0.73           | 5/19 ± 0.90         | 4/29 ± 0.73                  |
|           | ‘Milotai kései’ | 4/24 ± 0.63 | 4/27 ± 0.56           | 5/5 ± 0.56          | 5/13 ± 0.80                  |
| Hungary   | total        | 4/18 ± 0.51  | 4/26 ± 0.41           | 4/28 ± 0.57         | 5/6 ± 0.52                   |
| Iran      | ‘ChandlerI’  | 4/9 ± 0.70   | 4/13 ± 0.73           | 4/20 ± 0.73         | 4/22 ± 0.71                  |
|           | ‘Jamal’      | 3/30 ± 0.82  | 4/4 ± 0.92            | 4/11 ± 0.97         | 4/10 ± 0.98                  |
|           | ‘RDM’        | 4/20 ± 0.68  | 4/27 ± 0.96           | 5/5 ± 0.98          | 4/26 ± 0.68                  |
| Iran      | total        | 4/9 ± 0.54   | 4/14 ± 0.63           | 4/21 ± 0.65         | 4/20 ± 0.56                  |
| Grand total|              | 4/13 ± 0.40  | 4/20 ± 0.42           | 4/24 ± 0.44         | 5/2 ± 0.40                   |

The variety ‘Jamal’ needed less GDD for pollen shedding initiation; therefore, its value is the base. ‘Chandler’ in Hungary needed the 23.9 °C GDD on Tb0 to start its pollen shedding. ‘Milotai kései’ needed 98.3 °C more GDD, and catkins of ‘Milotai 10’ required the most GDD on Tb0 (101.6 °C). In Iran the varieties had to accumulate more heat to start their pollen shedding. ‘Chandler’ grown in Iranian cumulation than the early-leafing ‘Jamal,’ and the cultivar ‘RDM’ required 207.2 °C (Table 5). Table 5 indicates the GDD data needed to accumulate starting pistillate receptivity from the earliest leafing varieties of each country.

The start of pollen shedding had the highest correlation with base temperature of 0 °C in both countries (Fig. 3). In Hungary, $r^2 = 0.57$, while in Iran $r^2 = 0.51$ at the base temperature of 0 °C (Fig. 4).
Fig. 1 Coefficient of determination for leafing date as independent variable and growing degree days (GDD) as dependent variable

![Graph showing R² for leafing date as independent variable and GDD as dependent variable.](image)

Fig. 2 Scatter plot and regression between accumulated growing degree days (GDD) (5.5°C) and leafing date in Iran (a) and Hungary (b)

![Scatter plots showing GDD and leafing date relationship in Iran and Hungary.](image)

Table 5 Average growing degree days (GDD) for leafing date, pistillate receptivity start, and pistillate receptivity end in Hungary and Iran

| Country   | Cultivar          | GDD for leafing with respect to earliest cultivar | GDD for pistillate receptivity start with respect to leafing | GDD for pistillate receptivity end with respect to pistillate start |
|-----------|-------------------|--------------------------------------------------|------------------------------------------------------------|---------------------------------------------------------------|
| Hungary   | ‘Chandler’        | 59.1 ± 1.48                                      | 92.6 ± 2.55                                                | 107.6 ± 1.97                                                  |
|           | ‘Milotai 10’      | 0.0 ± 0.00                                       | 68.4 ± 1.90                                                | 99.5 ± 1.53                                                  |
|           | ‘Milotai kései’   | 99.3 ± 1.20                                      | 123.0 ± 2.49                                               | 92.2 ± 1.69                                                  |
| Hungary total |                  | 52.8 ± 1.21                                      | 94.7 ± 1.40                                                | 99.8 ± 1.01                                                  |
| Iran      | ‘Chandler’        | 92.1 ± 1.71                                      | 130.6 ± 2.51                                               | 102.2 ± 1.96                                                 |
|           | ‘Jamal’           | 0.0 ± 0.00                                       | 95.5 ± 2.78                                                | 82.3 ± 1.81                                                  |
|           | ‘RDM’             | 207.2 ± 2.74                                     | 78.8 ± 2.54                                                | 90.1 ± 2.26                                                  |
| Iran total |                  | 99.8 ± 1.83                                      | 101.6 ± 1.53                                               | 92.3 ± 1.16                                                  |
| Grand total |                 | 78.4 ± 1.16                                      | 98.5 ± 1.04                                                 | 96.2 ± 0.77                                                  |
Fig. 3 Coefficient of determination for start of pollen shedding as independent variable and growing degree days (GDD) with different base temperatures as dependent variable.

Fig. 4 Scatter plot and regression between accumulated growing degree days (GDD) (0 °C) for pollen shedding in Iran (a) and Hungary (b).

climatic conditions had to collect 133.5 °C, and ‘RDM’ had to accumulate 354.5 °C to start this phenological stage.

To complete the pollen shedding stage, the Hungarian-grown varieties needed less GDD than those varieties grown in Iranian conditions. Values are depicted in Table 6.

The start of pistillate receptivity had the best correlation with base temperature of 5.5 °C in both countries (Fig. 5). The coefficient of determination for the start of pistillate receptivity on base temperature of 5.5 °C was $r^2 = 0.82$ and $r^2 = 0.70$ for Hungary and Iran, respectively (Fig. 6).

This study confirms the findings of other researchers (Baker et al., 1986; Gallagher 1979; Sayed 1995; Stinner et al. 1974) that changes in the phenological stages are the best markers for the fruit species for forecasting their behaviour with the increasing outside air temperature; however, there are differences in the base temperature values among the species, cultivars, and phenological states (Borges et al. 2017; Kerr et al. 1981; Rafael and Biasi 2016; Ribeiro et al. 2009; Salinger and Kenny 1995; Souza et al. 2011; Taghavi et al. 2017). The strongest correlation of the observed phenological data was always on the same threshold values in both countries; in the case of leafing, the best correlation was at $T_{b5}$. This value is higher than the amount predicted for grape cultivars ‘Chardonnay’ ($T_{b} = 2.1$ °C) and ‘Cabernet Sauvignon’ ($T_{b} = 4.3$ °C), kiwifruit ‘Golden King’ ($T_{b} = 4.3$ °C), plum ‘Gulf Blaze’ ($T_{b} = 2.2$ °C), pear ‘Smith’ ($T_{b} = 4.4$ °C), peach ‘Tropic beauty’ ($T_{b} = 2$ °C) (Rafael and Biasi 2016), and hazelnut cultivars ($T_{b} = 2$ °C) (Taghavi et al. 2017). The kiwifruit cultivar ‘Hayward’ ($T_{b} = 10$ °C, Kerr et al. 1981; Salinger and Kenny 1995; $T_{b} = 8.2$ °C, Rafael and Biasi 2016), the pear cultivar ‘Packham’s’ ($T_{b} = 8.2$ °C, Rafael and Biasi 2016), the plum cultivar ‘Letícia’ ($T_{b} = 6.2$ °C, Rafael and Biasi 2016), the grape cultivars ‘BRS Victo-
Table 6 Growing degree days (GDD) for pollen shedding start with respect to earliest cultivar and pollen shedding end with respect to pollen shedding start in Hungary and Iran

| Country   | Cultivar      | GDD for pollen shedding start with respect to earliest cultivar | GDD of pollen shedding end with respect to pollen shedding start |
|-----------|---------------|---------------------------------------------------------------|----------------------------------------------------------------|
| Hungary   | ‘Chandler’    | 23.9 ± 2.46                                                   | 169.2 ± 2.46                                                    |
|           | ‘Milotai 10’ | 101.6 ± 2.40                                                  | 162.4 ± 2.40                                                   |
|           | ‘Milotai kései’ | 98.3 ± 2.22                                             | 140.8 ± 2.22                                                   |
|           | Hung Mg total | 0 ± 1.36                                                      | 157.4 ± 1.36                                                   |
| Iran      | ‘Chandler’    | 133.5 ± 1.68                                                  | 129.6 ± 1.52                                                   |
|           | ‘Jamal’       | 0 ± –                                                        | 117.5 ± 2.15                                                   |
|           | ‘RDM’         | 354.5 ± 2.04                                                  | 171.1 ± 2.04                                                   |
| Iran Mg total | –            | 155.3 ± 1.23                                                  | 137.6 ± 1.18                                                   |
| Grand total | 0            | 112.1 ± 0.93                                                  | 147.8 ± 0.92                                                   |

Fig. 5 Coefficient of determination for growing degree days (GDD) from start of pistillate receptivity to leafing date as dependent variable and pistillate start date as independent variable

Fig. 6 Scatter plot and regression between accumulated growing degree days (GDD) (base temperature of 5.5°C) of period between pistillate receptivity and leafing date in Iran (a) and Hungary (b)
ria’ (Tb=10°C, Borges et al. 2017) and ‘Niagara Rosada’ (Tb=8°C, Ribeiro et al. 2009), as well as the nectarine ‘Sunblaze’ (Tb=8°C, Souza et al. 2011), were found to require higher base temperature values than the Persian walnut cultivars involved in our study. The value of 5.5°C as the base temperature for leafing confirms the report of Dreyer and Maugé (1986) that development of the terminal buds on ‘Pedro’ and ‘Franquette’ in French climate conditions was most rapid at less than 12°C. Other researchers (Crepinšek et al. 2009; Hidalgo-Galvez et al. 2018) reported negative coefficients for correlation between the daily mean temperature (without a threshold level) and days needed to reach the required phenological stage.

In this trial there were positive correlation coefficients (0.52 for both countries) when correlations between the heat accumulation and the calendar days were examined. This indicates that the more heat accumulation a cultivar can collect during a day above a threshold level, the less time is needed for reaching the phenological stage.

Pollen shedding showed the strongest correlation with Tb, and pistillate opening had the highest coefficient value on Tb5.5. Both Tb values are lower than those observed for other fruit species except for hazelnut cultivars, which had 2°C as the base temperature (Taghavi et al. 2017).

The walnut cultivars from both countries need less heat accumulation than some wine grape and kiwifruit cultivars (Rafael and Biasi 2016). The walnut cultivars grown in Hungarian climatic conditions needed 20% to 30% less GDD demand for leafing than those under the Iranian conditions. The highest GDD demand was for the late-leaving ‘RDM’ (207°C) walnut cultivar grown in Iran. During the pistillate receptivity, the investigated cultivars required similar heat accumulation in both countries (Table 4), while for pollen shedding the cultivars grown in Hungarian climatic conditions needed less GDD than the cultivars planted in Iran (Table 5).

The walnut cultivars in this trial required more GDD for pollen shedding than for the pistillate period. Pollen shedding of early-flowering forestry species (e.g., Betula, Quercus) had a long period during years with cold spring weather (García-Mozo et al. 2006; Hidalgo-Galvez et al. 2018).

Conclusions

The Persian walnut cultivars investigated needed the same threshold temperature in Hungary and Iran to leaf out (Tb5.5, r² = 0.52) and blossom the male (Tb0, r² = 0.5 in Iran, r² = 0.57 in Hungary) and female flowers (Tb5.5, r² = 0.80 in Iran, r² = 0.72 in Hungary). Although the threshold levels were similar for the cultivars derived from the Hungarian and Iranian assortments, they needed different heat accumulation to reach the phenological stages. The Iranian cultivars needed more heat accumulation to initiate leafing and start the pistillate opening and pollen shedding periods. For leafing, the walnut cultivars grown in Hungary needed lower Tb values (grand total: 52.8°C) than cultivars cultivated in Iran (grand total: 78.4°C). Selected cultivars grown in Iran needed less heat accumulation for starting the pistillate opening period (grand total: 98.5°C) than for starting the pollen shedding period (grand total: 112.2°C). This is in contrast to the cultivars grown in Hungary, where the pistillate opening period needed less heat accumulation (grand total: 74.6°C) than for pollen shedding (grand total: 94.7°C). By using GDD, phenological stages during spring can be forecasted.

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Conflict of interest

G. Bujdoso, A. Soelimani, B. Illes, and D. Hassani declare that they have no competing interests.

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