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Heat Requirements of *Prunus mume* Cultivars for Flowering

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Abstract: Heat requirements play an important role in plant flowering, and control the flowering period of woody ornamental plants to a certain extent. In this study, the perennial potted seedlings of four typical *Prunus mume* cultivars 'Xiaolve', 'Baixuzhusha', 'Fenghou' and 'Danfenghou' were used as materials. The way of regulating the cultivation temperature is adopted to achieve the purpose of relieving the natural dormancy and forcing the blooming of *P. mume*. Its content includes the research on the heat requirements of *P. mume* cultivars widely planted in Beijing, and the analysis of the influence of different facility cultivation temperatures on the flowering characteristics of *P. mume*, providing a theoretical basis for further exploring the cultivation techniques of *P. mume* bonsai flowering regulation. The results showed that, according to the Growing degree-hour model, the HR of 'Xiaolve', 'Baixuzhusha', 'Fenghou' and 'Danfenghou' flower buds were 3583.70 GDH℃, 3217.30 GDH ℃, 3996.50 GDH ℃, 4732.20 GDH ℃, respectively. According to the effective accumulated temperature model, the HRs of above cultivars were 350.65 ℃, 319.30 ℃, 510.30 ℃, 558.50 ℃, respectively. In addition, the temperature of different cultivation facilities did not significantly change the flowering quality such as flower diameter and fragrance. Temperature also affects the growth and development speed, affecting the flowering time. Under the facility environment with higher temperatures, the flowering process is faster and the flowering period is shorter.

Keywords: *Prunus mume*; regulation of flowering period; heat requirements; dormancy release; flower bud germination

1. Introduction

Flowering regulation refers to a series of measures to artificially change the growth environment conditions according to the natural flowering habits and growth development laws of plants to make them flower earlier or later. It is an indispensable and important part of the modern flower industry [1]. Temperature is a key factor af-fecting the regulation of flowering, especially for woody ornamental plants [2,3]. During the dormancy period of flower buds and the development stage of flower buds, the temperature has different effects on plant growth and flowering [4]. Sufficient low-temperature can relieve flower bud dormancy, while insufficient low-temperature accumulation can lead to failure to achieve flowering, even under suitable growth conditions [5,6]. During the flower bud development stage, suitable temperature ac-cumulation can promote the flowering and growth of plants [7]. Therefore, an in-depth understanding of the role of temperature in flowering regulation is of great significance for improving the yield, quality, and cultivation efficiency of woody ornamental plants, and can also promote the sustainable development of the flower industry.

Prunus mume Sieb. et Zucc. is a deciduous ornamental tree belonging to the genus Prunus in the family Rosaceae. It originated in China and has a cultivation history of 3,000 years [8] The flowering period of P. mume in the Southern China is late winter and early spring, and it is one of the earliest ornamental plants to open. Loved for its charming, fragrant flowers and quaint tree form, it is widely planted. However, the climatic conditions for the growth of P. mume are very limited [9], and it is difficult to meet ornamental needs in other specific periods. Temperature is a key factor affecting the growth and flowering of P. mume [10]. Knowing the minimum demand for heat accumulation of different P. mume cultivars is an important basis for flowering regula-tion, so that precise regulation of flower supply time can be realized. By mastering the temperature law of P.

mume growth and development, and taking appropriate tem-perature raising measures in the regulation of flowering period, it is possible to pro-mote flowering and prolong the flowering period. Therefore, for the modern P. mume industry, it is very important to grasp the role of temperature in flowering regulation, which can improve the production efficiency and promote the development of P. mume industry.

Heat requirements refers to the effective heat accumulation required for perennial deciduous fruit trees to release their physiological dormancy until they bloom in spring [11]. To better quantify the amount of heat requirements for flowering, researchers have developed heat requirements models. Currently, the most widely used and common models are the Growing degree-hour model and the effective accumulated temperature model. Among them, the growth degree-hour model was defined by Anderson and Seeley in 1992 as the heat unit equivalent to a given temperature per hour, that is, the growth degree-hour (GDH°C) [12]. In this model, 4.5°C is taken as the lower limit temperature of plant growth, and 25°C is taken as the upper limit temper-ature to calculate the temperature accumulation of plants during the growth and de-velopment stages. Gu proposed a phenology observation model in his study, which changed the time threshold for calculating accumulated temperature from days to minutes, and improved the accuracy of calculation results by increasing the amount of data [13]. However, due to the need to analyze a larger amount of data, the model requires higher computing resources and technical support. The effective accumulated temperature model is one of the models commonly used to study plant growth and heat demand. It refers to the cumulative value of the daily average temperature higher than the biological lower limit temperature. The model is based on the biological zero temperature of the plant [14]. By studying the accumulated temperature required by different crops and cultivars under different climatic conditions, we can better under-stand their growth patterns. Although heat requirement models have been widely used to study the growth, development and flowering of plants, so far, these studies have mainly focused on peaches [5,11], apples [15], pears [16] and other plants. However, there are relatively few studies on the heat requirements of P. mume cultivars. In this context, evaluating the heat requirements of P. mume cultivars and analyzing the effect of temperature on their flowering traits will provide a theoretical basis for the regula-tion of P. mume flowering period, which has practical application value for optimizing P. mume planting and improving P. mume production efficiency.

Therefore, this research has important practical application value. The purpose of this study is to explore the heat requirements of P. mume cultivars widely planted in Beijing. Growing degree-hour model and effective accumulated temperature model were used to measure the heat accumulation required from the release of dormancy to flowering, and the effect of temperature on the flowering of plum blossoms was ana-lyzed. The result can provide a theoretical basis for the regulation of P. mume flowering period, and also provide new ideas and methods for similar research.

2. Materials and Methods

2.1. Experimental Time and Place

The experiment was carried out from December 2021 to January 2022. The experimental sites are Meiju greenhouse (40°01'N, 116°35'E) and the Garden Experimental Teaching Demonstration Center - Sanqingyuan greenhouse (40°00'N, 116°34'E), which located at the Beijing Forestry University in Beijing, China.

2.2. Experimental Material

5-8-year-old P.mume 'Xiaolvcalyx', ' Baixuzhusha', 'Fenghou', 'Danfenghou' potted seedlings, 9 of each cultivar, 27 in total. The plants were robust, compact, free of diseases and insect pests, branches were evenly distributed, buds were full, and uniform in size, with a ground diameter of about 2.5 cm to 4.1 cm and a plant height of about 130 cm.

2.3. Method

2.3.1. Temperature Statistics

The temperature and humidity recorder (measuring range is between -40°C and 80°C, and the temperature accuracy is ±0.1°C) was placed in the greenhouse at a height of 1.5 m from the ground, and the ambient temperature in the greenhouse was recorded every 30 min. The release of natural dormancy period is the beginning of temperature, and the recording ends when all four cultivars decay. Two greenhouses were set up for temperature treatment in the experiment, and the four *P. mume* cultivars that had completed low-temperature accumulation were placed in the following two greenhouses for conventional cultivation, with 3 plants for each cultivar in the greenhouse. Observe the germination rate of flower buds under different temperature treatments, as well as the flowering status and phenological period of different *P. mume* cultivars.

2.3.2. Determination of Heat Requirements

Based on the growth-hour model [12] and the effective accumulated temperature model [17], the heat requirements for flowering of four *P. mume* cultivars were estimated.

1.Growing degree-hour model:

$$GDH°C = \sum_{i=1}^{n} T_{GDH} \tag{1.1}$$

$$T_{GDH} = \begin{cases} 0, & T \leq 4.5°C \\ T - 4.5, & 4.5°C < T < 25.0°C \\ 20.5, & T \geq 25.0°C \end{cases} \tag{1.2}$$

Among them, GDH°C represents the effective heat accumulation required for dormancy to be released to 50% of flower bud germination, TGDH represents the effective low temperature per hour, and *T* represents the temperature recorded per hour.

2. Effective accumulated temperature model:

$$D = \sum_{i=1}^{n} (T1 - T2) \tag{1.3}$$

Among them, *D* represents the effective heat accumulation required from dormancy release to flower bud germination, *T1* represents the daily average temperature, and *T2* represents biological zero.

2.3.3. Observation of Phenology and Determination of Flowering Index

The plants of each cultivar were observed at around 8:00 a.m. each day, and 3 replicate groups were set up for each cultivar, and each replicate group contained 3 (about 30 buds) branches with similar root thickness, health, and full flower buds. The statistical results were obtained from average value. The plants were continuously observed and record the phenological data after being removed in greenhouses. According to the different stages of single flower blooming (Tight bud stage、Current color stage、Loose bud stage、Initial flowering stage、Full bloom stage、Decline stage) [18]. the characteristics of each flowering process stage are shown in Table 1:

Table 1. Morphological characteristics of flowering process of *P. mume.*

flowering period	T characteristics
Tight bud stage	The calyx is slightly split and tightly encases the buds, the top of the calyx is slightly cracked to 1/4, and the petals can be seen, the buds are tight, with a small opening at the top, and dark red petals can be observed at the opening.

Current color stage	The calyx cracks more, and the calyx cracks to about 1/2, and the calyx tightly encloses the flower bud. The petals are gradually rounded.
Loose bud stage	Calyx splits, calyx retreats to 1/3 of bud. The buds are enlarged and softer, the inner petals are visible at the top of the bud, the outer petals are slightly softer, and the buds show a lighter color than they were in vivid color.
Initial flowering stage	There are multiple layers of loose petals growing inside the buds. The petals are lighter in color than those at the bud loosening stage. The outer petals gradually unfold obliquely upwards, and the inner stamens are clearly visible. The early blooming stage is the date when about 5% of the flowers bloom.
Full bloom stage	The petals are fully opened to the maximum flower diameter, the outer petals are flat or slightly stretched downward, the filaments are radial, and the stamens are fresh and radial. The full bloom period is the date when about 25% of the flowers bloom.
Decline stage	Part of the petals wilt and fall off, some anthers fall off, the flowers lose their shape, and the petals shrink and lose their ornamental value. The decay period is the date when 75% of the petals begin to change color and drop petals.

There were 10 flowers of different cultivars in different flowering stages, and 3 repeated groups were set up to measure and record the morphological data of flower buds and flowers, and to count the flowering traits, such as flowering period, flower diameter, and flowering rate. The observation indicators are as follows:

Flower diameter: the diameter of the flower when it is fully bloomed (accurate to 0.01 cm), measured by the cross method with a vernier caliper.

Flowering amount = initial flowering stage + full blooming stage + decline stage

Flowering rate (%) = (flowering amount/total amount) × 100%

2.4. Data Processing and Analysis

The research process used Microsoft Excel 2019 software for data collation, SPSS26.0 statistical software for data analysis, and OriginPro 2018 software for histogram drawing.

3. Results

3.1. Temperature Statistics

December 17, 2021 were as the starting point for temperature analysis. On January 8, 2022, when four cultivars of 'Xiaolve', 'Baixu Zhusha', 'Fenghou', and 'Danfenghou' all entered the full flowering period, the temperature records ended. As shown in Figure 1, according to the analysis of the daily maximum temperature, the minimum high temperature and the whole point temperature, the average temperature in the greenhouse in the T2 treatment was significantly higher than that in the T1 treatment. During this time period, the average temperature of T1 treatment was 15.95°C, the average humidity was about 62.34%, and the highest temperature was 27.8°C. The average temperature of the T2 treatment was 19.79°C, the average humidity was 56.13%, and the highest temperature can reach 32.7°C. The difference between the daily average temperature of the two facilities T1 and T2 is 3.84°C.

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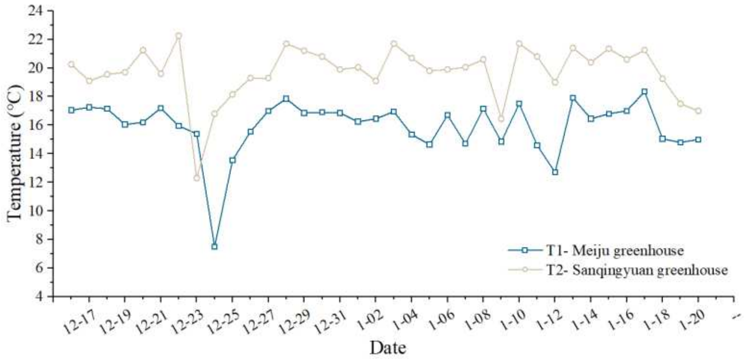

Figure 1. Temperature changes in different greenhouse.

3.2. Heat Requirements

According to the flowering period observations of four *P. mume* cultivars and the measured growth environment temperature, this study used the growth time model and the effective accumulated temperature model to obtain the calorific value for flowering of different *P. mume* cultivars. The results are shown in Table 2.

When estimated by the Growing degree-hour model, the heat requirements of the four *P. mume* cultivars were concentrated in the range of 3200-4750 GDH℃, and the heat requirements of 'Danfenghou' was the highest at 4743.2 GDH℃, which was significantly higher than that of other cultivars; 'Fenghou', 'Xiaolucalyx' were next, 3996.5 GDH℃ and 3583.7 GDH℃, respectively; flower buds of 'Baixuzhusha' had the lowest heat requirements, 3217.3 GDH℃. When estimated by the Effective accumulated temperature model, the order of heat requirements was consistent with that estimated by the growth-hour model, and the range of heat requirements for the four *P. mume* cultivars was concentrated in the range of 310-560°C.

Table 2. Heat requirements of buds of different *Prume mume* cultivars calculated by different models.

cultivar	Growing degree-hour model (GDH ℃)	Effective accumulated temperature model (℃)
'Xiaolve'	3583.70c	350.65c
'Baixuzhusha'	3217.30d	319.30d
'Fenghou'	3996.50b	510.30b
'Danfenghou'	4743.20a	558.50a

Note: Different lowercase letters in the same column indicate significant differences at the 0.05 level among different treatments ($P<0.05$).

3.3. Effects of Temperature in Different Facilities on the Flowering Rate

After satisfying the low-temperature accumulation, on December 16, 2021, they were moved into two greenhouses with different cultivation environments, T1 (Meiju greenhouse) and T2 (Sanqing greenhouse), to observe and record the flowering rate. The influence of different environmental temperatures on the flowering rate of different *P. mume* cultivars is shown in Table 3. After greenhouse cultivation, the treatments of the two environmental temperatures can promote the germination of flower buds to varying degrees, and the flower buds all expand and open normally. The cultivation environment with higher temperature can better promote flower bud germination. Among them, 'Baixuzhusha' *P. mume* had the highest flowering rate in T2 treatment, and the germination rate could reach 72.02% when the flowering was stable, which was 5.38% higher than that in T1 treatment; The flowering rate of 'Fenghou' was 60.78% and 59.20%, respectively increased by 7% and 10.18% compared with T1 treatment; the flowering rate of 'Fenghou' was the least, and increased by 10.04% under T2 treatment compared with T1 treatment. It can be seen that the growth and flowering of *P. mume* are closely related to the temperature of cultivation facilities. When the chilling requirements of different *P. mume* cultivars were met, the flowering rate of T2 treatment is significantly higher than that of T1 treatment.

Table 3. Effects of different facility temperatures on flowering rate of different *P. mume* culticars.

Treatment	Flowering rate （%）			
	'Xiaolve'	'Baixuzhusha'	'Fenghou'	'Danfenghou'
T1	56.80b	68.34b	51.08b	53.73b
T2	60.78a	72.02a	56.21a	59.20a

Note: Different lowercase letters in the same column indicate significant differences at the 0.05 level among different treatments (P<0.05).

3.4. Effects of Temperature in Different Facilities on Flowering Quality

The results of greenhouse cultivation are shown in Table 3. The flowering quality of *P. mume* cultivars such as flower diameter and fragrance did not change significantly with the temperature of the facility. During the flowering process, there is no phenomenon of flower abortion or abnormal development, and the overall flowering is neat and has a certain ornamental value. Among them, the flower diameters of 'Xiaolve' and 'Baixuzhusha' were very small under the temperature treatments of the two facilities, and the flower diameters of 'Fenghou' and 'Danfenghou' under the T2 treatment were slightly larger than those under the T1 treatment, respectively increasing 6.84%, 16.39%.

Table 4. Effects of different facility temperatures on flower diameter of different *P. mume* culticars.

Treatment	Flowering diameter （%）			
	'Xiaolve'	'Baixuzhusha'	'Fenghou'	'Danfenghou'
T1	1.94±0.15a	2.19±0.24a	2.34±0.15b	2.44±0.31b
T2	1.92±0.20a	2.15±0.14a	2.50±0.11a	2.84±0.13a

Note: Different lowercase letters in the same column indicate significant differences at the 0.05 level among different treatments (P<0.05).

3.5. Effects of Temperature in Different Facilities on the Development Process

In this study, the phenological stages of four cultivars under two temperature treatments were observed, and the flowering process is shown in Figure 2. It was found that the tight bud stage and full flowering stage of each cultivar lasted longer, and the flowering stage mainly concentrated from mid-December 2021 to mid-January 2023. The single flower flowering stage of Fenghou' under T1 treatment was 21.1 d, 23.2 d, 26.2 d, 25.5 d, respectively, and the single flowering period under T2 treatment were 15.7 d, 16.1 d, 22.5 d, 20.2 d. The flowering process of different cultivars was significantly affected by the environmental temperature. The T2 treatment flowered earlier than T1, and the flowering process was faster, the time of each stage was compact, and the flowering period was shorter; For ornamental flowering period is longer. At this time, the *P. mume* growing in the outdoor natural environment did not open.

Due to the difference in flowering time caused by the variety itself, the flower bud dormancy end period and flowering process of different *P. mume* cultivars are different. The flowering period of 'Xiaolve' and 'Baixuzhusha', which are early-flowering *P. mume* cultivars, have the same overall difference. They opened one week earlier than 'Fenghou' and 'Danfenghou', which are late-flowering cultivars. Among them, ' Baixuzhusha ' had the earliest flowering period at the two facility temperatures, and 'Fenghou' lasted the longest. In addition, by observing the flowering process of four cultivars of *P. mume* on the tree body, we found that each cultivar has different ornamental value. After the *P. mume* enter the decay period, the leaves grow immediately, and the tree body enters a new round of nutrition again. period of growth and development.

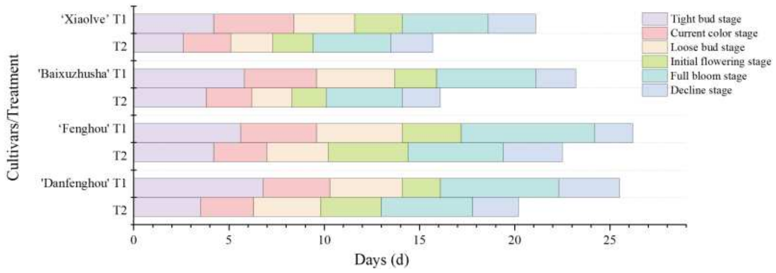

Figure 2. The time of the flowering process of different *P. mume* culticars.

4. Discussion

4.1. Heat Requirements

Flower buds need to accumulate a certain amount of effective heat to germinate and bloom when they are released from natural dormancy [19]. Taking the chilling and heat requirements as a reference, Spiegel-Roy and Alston studied the early and late maturity standards of 50 different genotypes of pear tree cultivars. There is a high correlation coefficient between the heat requirements and the flowering date of pear trees, and it is more effective to estimate the flowering period of pear trees with the heat requirements [16]. Gianfagna and Mehlenbacher found that apples bloom late because of their higher heat requirements, and concluded that heat requirements have a greater effect on flowering regardless of their genetic type [20]. After *P. mume* go through the dormancy period, when the daily average temperature is higher than 0°C and the accumulation reaches 230-250°C, they can enter the blooming stage [21]. In 2012, Cao Shu min et al. (2012) studied the relationship between flowering characteristics and effective accumulated temperature of garden trees and found that the effective accumulated temperature of *P. mume* 'Meiren' was 136.4°C [22]. Song Ping (2015) measured that the effective accumulated temperature of early-flowering cultivars such as 'Yudie' can bloom when it reached 60.5°C; 'Nanjinghong' can bloom when the effective accumulated temperature reached 132.5°C [23]. It can be seen that there are certain differences in the heat requirements among different species, among different cultivars of the same species, and for the same species in different years and regions. In this study, the estimation results of the Growing degree-hour model and the Effective accumulated temperature model are consistent in terms of heat demand ranking. It is concluded that the flower buds of 'Danfenghou' have the highest heat requirements, and the flower buds of 'Baixuzhusha' have the lowest heat requirements. Based on the experiment. when the dormancy of the flower buds was over, the temperature-raising measures can be used to meet the heat requirements of the cultivars, which can effectively promote flowering to achieve the purpose of advancing the flowering period. In actual production management, producers regulate the time of germination by increasing the temperature of the germination period.

4.2. Effect of Heat Requirements on Flowering Traits

In this study, when the flower buds were released from dormancy by low temperature, the temperature treatments of different facilities would affect the flowering of different cultivars. The flowering of *P. mume* are closely related to the temperature of the cultivation facilities. The higher the temperature, the earlier the germination and flowering. Among them, the flowering rate in the cultivation facility (T2) located in Sanqing greenhouse with higher temperature was significantly increased, but the flowering quality such as flower diameter and fragrance of each cultivar did not change significantly with the different temperature of the facility, and there was no flower abortion, developmental abnormalities. In addition, the influence of different environmental temperatures on the flowering process of different *P. mume* cultivars is more significant. In the setting environment with higher temperature, the flowering process was earlier and faster, and the time of each stage was compact and shorter. However, When the ambient temperature of the facility was low, the flowering process was slow and last for a long time, and the flowering period for viewing was long. which is consistent with previous studies on apples [24], pears [25], and peach trees [26]. In addition, Faust. et al. also found that the flowering time of apple buds was determined by the heat requirements when studying the root tip dominance of apple buds in winter dormancy [27]. Arora and Rowland found that prolonged heat accumulation promoted peach bud germination in August even when peaches did not experience low temperature accumulation [28]. It can be seen that the greenhouse cultivation environment after the dormancy is released plays a more critical role in flowering, and the inherent characteristics of the variety itself also affect its growth and flowering in promoting cultivation.

5. Conclusions

Grasping the heat requirements of different *P. mume* cultivars, increasing the temperature of the microclimate where the plants are located, relieving dormancy, and promoting flowering growth and development are the basis for successful cultivation of plants and the key to realizing flower supply in markets and exhibitions. In this study, based on the Growing degree-hour model, the heat requirements for flowering of 'Xiaolve', 'Baixuzhusha', 'Fenghou', and 'DanFenghou' were 3583.70 GDH℃, 3217.30 GDH℃, 3996.50 GDH℃, 4732.20 GDH℃, respectively. According to the Effective accumulated temperature model, the requirement heat were 350.65℃, 319.30℃, 510.30℃, 558.50℃, respectively. In addition, the temperature of different cultivation facilities did not significantly change the flower diameter, flower fragrance and other flowering quality of each variety, but the flowering process was faster and the flowering period was shorter in the setting environment with higher temperature. A long time. It is of wide application value to regulate the flowering period based on the heat requirements. In the cultivation process, it should not be carried out blindly according to the heat requirements, but should be gradually raised according to the specific growth conditions, otherwise the quality of flowering cannot be guaranteed.

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