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Temperature effects on seed germination in races of common beans (Phaseolus vulgaris L.)

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ABSTRACT. Temperature is one of the most important environmental factors, affecting establishment and crop development. Seed germination is particularly affected by temperature. The aim of this work was to evaluate the tolerance temperatures during germination in several bean cultivars. The seeds were submitted to temperatures ranging from 8 to 45°C in thermal block apparatus and primary root protrusion time. The number of germinated seedlings was scored for each cultivar and temperature. High temperatures (≥40°C and upper) strongly inhibit cultivar germination, but 'IAPAR-57', 'Guarumbê' and 'Iratim' appear to be more sensitive to high temperature stress than others. 'IAC Carioca 80SH' PP and 'IAPAR-57' were less tolerant to low temperatures. The thermal time model could describe, relatively well, the time-course of the cultivars isothermal germination, which differed in the thermal time amount required to germinate. 'IAC Carioca-Akyta' needs fewer degrees per day to achieve germination than others, whereas the cultivar 'Campeão-1' requires more thermal time.

Key words: bean, cardinal temperature, degrees per day, germinability, velocity.

RESUMO. Efeitos da temperatura na germinação de sementes em culturas de feijões comuns (Phaseolus vulgaris L.). A temperatura é um fator ambiental importante, afetando a germinação de sementes, o estabelecimento e o desenvolvimento de culturas. O objetivo deste trabalho foi avaliar as temperaturas de tolerância durante germinação em vários cultivares de feijão e determinar o valor de parâmetros térmicos para a germinação de cultivares. Sementes foram submetidas a temperaturas variando de 8°C a 45°C, em bloco termo-gradiente até a protrusão da raiz primária. Temperaturas altas (≥40°C ou mais) inibem fortemente a germinação dos cultivares. 'IAPAR-57', 'Guarumbê' e 'Iratim' parecem ser mais sensíveis à temperatura alta que outros. 'IAC Carioca 80SH' PP e 'IAPAR-57' foram menos tolerantes a baixas temperaturas. O modelo termal de tempo poderia descrescer relativamente bem o curso da germinação em isotermas dos cultivares que diferiram na quantia de graus-dia para germinar. 'IAC Carioca-Aktla' precisa de menos graus-dia¹ para alcançar a germinação que outros, O cultivar 'Campeão-1' requer mais graus-dia¹.

Palavras-chave: feijão, temperatura cardinal, graus por dia, germinabilidade, velocidade.

Introduction

The large genetic diversity in common bean races is followed by adaptations to different environments (Delgado et al., 1988). Temperature is one of the most important environmental factors, affecting crops’ establishment and development. Seed germination is particularly affected by temperature, which is widely reported in scientific literature. In general seed pattern, germination increases as temperature rises from a minimum (or base) to an “optimum” temperature or temperature range, then germination declines with increasing temperatures up to a “maximum” or “ceiling”, above which the seeds do not germinate. Minimum and maximum are the limit temperatures for seed germination, and these characteristics depend on the species, lot, seed dormancy, etc. Thus, different seed lots can be characterized by their cardinal temperatures, that is, the base, the optimum, and the maximum temperature (Labouriau, 1983).
As pointed by White and Montes (1993), the study of temperature dependence at seed germination in common bean is interesting for many reasons, such as: i) genotype selection for improved germination at low or high temperatures; ii) modelling crop development in response to air or soil temperature regime and iii) to understand bean phylogeny and evolution. Although the response of Phaseolus vulgaris plants to temperature may vary depending on the development stage and specific process (Franco et al., 1972), correlations of field and laboratory measurements of germination responses to different temperatures have been examined in several leguminous crop species. In alfalfa, for example, rapid germination and primary root growth at suboptimal temperatures in laboratory was positively correlated with high emergence at field conditions (Klos and Brummer, 2000). In soybean and common bean, the germination rate under low temperatures in the laboratory provided a good tolerance test for cold field conditions (Dickson and Boettger, 1984). Kolasinska et al. (2000) observed that soil temperature at sowing appeared to be the most important environmental factor influencing field emergence of common bean, allowing the differentiation of a seed lot with high field emergence potential.

Several authors have investigated the temperature effect on Phaseolus vulgaris seeds germination (Roeggen, 1987; Hucl, 1993; Zaiter et al., 1994; Otubo et al., 1996); the conclusions drawn from such investigations were: bean cultivars may have different reactions to temperature; seed germination of common bean under suboptimal temperatures have been strongly influenced by genotype, and some genotypes have been more tolerant to cold during germination than others.

When the relation between germination rate and temperature is linear, thermal time (or heat units) can be normalized on a common thermal parameters for cultivar germination.

Material and methods

Plant material

The following common bean (Phaseolus vulgaris L) cultivars were assayed: 'Rosinha G-2'; 'IAC-Carioca-80SH'; 'Vermelho 2157'; 'IAPAR- 57'; 'Rudá'; 'Aporé'; 'Campeão-1', and 'IAC-Carioca-Akytá'. The landraces Iratim and Guarumbé were also tested. The seeds were returned from the germplasm collection of the Centre of Genetic Resources of the Empresa Brasileira de Agropecuária, Brasília, DF, IAC (Instituto Agronômico de Campinas, São Paulo State), and Iapar (Instituto Agronômico do Paraná, Londrina, Paraná State), and they were propagated at the experimental garden of Instituto de Biociências, Universidade Estadual Paulista (Unesp), Rio Claro, São Paulo State. The cultivar 'IAC-Carioca-80SH' was also propagated at Unoeste, Presidente Prudente, São Paulo State, and that lot is hereinafter referred as to 'IAC-Carioca 80SH' PP, in contrast to the lot produced at Rio Claro, referred as to 'IAC-Carioca 80SH' RC. The seeds collected were treated with phosphine and stored in paper bags in acclimatized room (25 ± 2°C) during four months at 50% of UR.

Germination assays

The isothermal incubation was carried out on polypropylene trays lined with thick qualitative filter-paper strips saturated with distilled water and placed inside closed glass tubes (250 x 25 mm) in a temperature gradient block adapted from Labouriau and Agudo (1987). The block is made of ten vertical sets of aluminium tubes, and each set is a temperature station with five replicates. Thus, every temperature station contained five tubes with 30 seeds per tube. The temperature in the thermal stations was measured with PT100 thermistors, connected to an electronic thermometer JIK model SK 010 (JK Instrumentos, Piracicaba, São Paulo State). The temperature measurements precision was 0.1°C. Temperature readings of all stations were taken before each observation of the germination tubes, and fluctuations of the mean temperature in each thermal station ranged from 0.1-1°C. Prior to the counting, the tubes were removed from the respective thermal station and the plastic trays were pulled out of the tubes, allowing the seeds to be examined under diffuse white light. As soon as the
Temperature effects on seed germination

germination was recorded (2-5 minutes), the seeds were returned to the thermal-gradient block.

The assays were kept in darkness and germination scored at 24-h intervals; seeds were considered germinated once the primary root emerged and achieved geotropic curvature (Labouriau, 1983). The seeds were withdrawn as soon as recorded.

Analysis data

Germinability and germination rate

The final percentage of germinated seeds (germinability, $G$) was transformed in angular values and compared through analysis of variance. The LSD5% was calculated for the significant differences according to the Tukey’s test (Sokal and Rohlf, 1995).

The germination rate was computed as the reciprocal of the average germination time ($t_i$), with $t = \sum (n_i t_i) / \sum (n_i)$, where $n_i$ is the number of germinated seeds between two consecutive observations $t_i$ and $t_{i-1}$ (Labouriau, 1983). Germination rates were compared by stepwise exhaustive comparisons of isotherm pairs (two-tailed Wilcoxon test) (Sokal and Rohlf, 1995). The distributions of isothermal germination frequencies ($f_i$) were computed from the formulae $f_i = n_i / \Sigma n_i$. The synchronization index ($U$, in bits) was computed as $U = -\sum f_i \log f_i$ (Labouriau and Agudo, 1987). The optimum temperature was the one at which both highest germinability and germination rate were observed.

T-base and thermal time calculation

For each line, the isothermal replicates were pooled and mean cumulative germination percentages were plotted against time. The isotherms were subsequently fitted by Weibull function (Dumur et al., 1990):

$$y = M[1 - \exp (-k(x-c)^r)]$$

Where: $y$ = cumulative germination at time $t$; $M$ = maximum germination; $k = \text{germination rate}; z = \text{lag in germination time};$ and $c = \text{shape parameter}$.

Times to 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% were obtained from such a function by calculation at each temperature. The rate of germination was, then, modelled, based on concepts developed by Garcia-Huidobro et al. (1982); therefore, in suboptimal temperature range, a thermal time (or degrees-day) approach can be used to find the germination times at different suboptimal temperatures:

$$\theta_g = (T - T_b) / t_g \Rightarrow 1/t_g = (T - T_b)/\theta_g$$

where: $\theta_g = \text{amount of thermal time to complete germination of a given fraction (e.g., 50%)}$; $T = \text{temperature}; T_b = \text{base temperature};$ and $t_g = \text{time to complete germination of a percentage } g$ (Bradford, 1995; Grundy et al., 2000).

Thus, the reciprocal of the times to germination (GR) for the different percentages (10% to 90%) estimated as described above were plotted against $T$ to estimate $\theta_g$ (the reciprocal of the slope of the linear regression of GR on T) and $T_b$ (the intercept on the temperature axis). Then, in order to find a common $T_b$ to each cultivar, all the $1/t_g$ values were regressed on temperature and different values of $T_b$ (temperature value when $1/t_g = 0$) were tried, until the highest correlation coefficient was obtained. This value was, then, used to calculate $\theta_g$ for each germination record, according to equation above, producing the points at Figure 5 ($G\% \times \theta_g$). The curves displayed in the Figure 6 were obtained from the actual measured values of thermal time ($\theta_r$, the slopes of the relationship between $1/t_g$ and T). The $\theta_r$ values calculated for a given germination percentage (10% to 90%) were transformed to log and plotted against probit $G\%$, with log $\theta_r$ in the abscissa:

$$\text{probit}(G\%) = 5 + 1/\sigma(\theta_r - \mu)$$ (Finney, 1952)

Where: $\sigma$ and $\mu$ are respectively the standard deviation (the reciprocal of the slope of the regression of probit(G%) on T) and mean (temperature corresponding to probit = 5) of the $\theta_r$ distribution.

At temperatures above the optimum, the amount of points was not enough to try a thermal time approach. Thus, confidence intervals ($\alpha = 0.05$) were determined for $G\%$, in order to search for the upper temperature limit, in which the confidence intervals intercept the temperature axis (Labouriau and Osborn, 1984).

Results and discussion

Germinability and germination rate (reciprocal of the average time) values for nine isotherms are displayed in Figure 1. The germination was null at the highest temperatures (39.3 and 44.4°C), as well as at 8.3°C. The cultivar 'Vermelho 2157' germinated at 8.3°C, although this germination was insignificant when compared to cultivars from temperate regions such as 'Volare' and 'G.N. Tara', that germinate well at 8°C (Zaiter et al., 1994).
Figure 1. Germinability (dark squares) and germination rate (open squares) temperature dependence of different cultivars of *Phaseolus vulgaris*. Germination rate is the reciprocal of the average time to germination. Capital letters indicate optimum temperatures for germinability; small letters indicate the highest germination rate values within the optimum range of germinability.
The germination optimum range, which means the temperature at which germination is faster (Bradford, 2002) and germinability, higher, was 18 to 31°C for cultivars 'IAC Carioca 80SH', 'Vermelho 2157' and 'Aporé'; and 22 to 31°C for cultivars 'Rosinha G2', 'IAPAR-57', Guarumbé, and 'Campeão-1' (Table 1). For the cultivars 'IAC Carioca-Akytá' and 'Rudá' the optimum interval to germination ranged from 27 to 35°C and 22 to 35°C, respectively. The widest temperature interval of optimum germination was observed in the cultivars 'IAC Carioca 80SH', 'Vermelho 2157', 'Rudá', and 'Aporé' (13°C), whereas the narrowest interval containing the optimum isotherms occurred in the cultivar Iratim.

On the other hand, germination rates exhibited higher temperature dependence than germinability. The germination rate tended to linearly increase with the temperature marked in the infra-optimum range. In the supra-optimum interval, rates dropped with temperature at a faster pace than increase rates with rising temperature. A similar pattern is shared by several species, such as tomato (Labouriau and Osborn, 1984) and Indian gherkin (Santos and Cardoso, 2001).

The calculation of the maximum temperature (Tm) to cultivars germination was difficult, due to the relatively sharp decrease in the germination percentage at high temperatures, thus the upper germination temperature limits of the bean cultivars studied here were represented by temperature intervals of nearly 4°C (Table 1). In order to find a maximum temperature, the criterion adopted for Tm is the highest temperature in which the confidence intervals (p = 0.05) of germinability intercept the temperature axis (G = 0%) (Labouriau and Agudo, 1987). The cultivars did not differ much from each other concerning Tm interval, which ranged from 35 to 39°C, with exception of the cultivars 'IAPAR-57', Guarumbé and Iratim, whose Tm was between 31 and 35°C (Table 1). It was also observed that temperatures around and higher than 40°C had deleterious effects on the seeds. This agrees with Pena-Valdivia et al. (2002) who, working with common bean cultivars from México, reported that high temperatures (35–45°C) have a positive effect on germination breaking of wild cultivars dormancy, but deteriorated the seeds of domesticated lines which did not exhibit dormancy.

Since germination tended to be progressively delayed at temperatures below 27°C in all cultivars, the thermal interval from 12.5 to 22°C was taken as the “sub-optimum” range and employed to find the base temperature (Tb) in each cultivar. The germination time courses of the isotherms in the infra-optimum range were fitted through Weibull function of parameters M, k, z, and c (see Material and Methods), whose values are in Table 2. Values of c around 3.6 suggest that the germination frequency distribution is symmetrical, while higher or lower values indicate negatively or positively skewed distribution, respectively (Bahler et al., 1989). Thus, taking into account the values of the shape parameter c, the cumulative germination curves show deviations from normality, and germinations are concentrated in the left-hand of the overall mode, chiefly at 16, 18, and 22°C. The lag in germination (parameter z) decreases as temperature rises, which means that germination is delayed at lower temperatures.

### Table 1. Experimental cardinal temperatures for seed germination of different cultivars of Phaseolus vulgaris (T<sub>o</sub> = optimum temperature; T<sub>m</sub> = maximum temperature; T<sub>b</sub> = minimum temperature).

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>temperature range (°C)</th>
<th>minimum</th>
<th>Optimum</th>
<th>maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>'IAC-Carioca 80SH RC'</td>
<td>8 ≤ T° &lt; 13</td>
<td>18 ≤ T° ≤ 31</td>
<td>35 ≤ T° ≤ 39</td>
<td></td>
</tr>
<tr>
<td>'IAC-Carioca 80SH PP'</td>
<td>16 ≤ T° &lt; 18</td>
<td>18 ≤ T° ≤ 31</td>
<td>35 ≤ T° ≤ 39</td>
<td></td>
</tr>
<tr>
<td>'Rosinha G2'</td>
<td>8 ≤ T° &lt; 13</td>
<td>22 ≤ T° ≤ 31</td>
<td>35 ≤ T° ≤ 39</td>
<td></td>
</tr>
<tr>
<td>'IAPAR-57'</td>
<td>13 ≤ T° &lt; 16</td>
<td>22 ≤ T° ≤ 31</td>
<td>35 ≤ T° ≤ 39</td>
<td></td>
</tr>
<tr>
<td>Guarumbé</td>
<td>8 ≤ T° &lt; 13</td>
<td>22 ≤ T° ≤ 31</td>
<td>35 ≤ T° ≤ 39</td>
<td></td>
</tr>
<tr>
<td>'Rudá'</td>
<td>8 ≤ T° &lt; 13</td>
<td>22 ≤ T° ≤ 31</td>
<td>35 ≤ T° ≤ 39</td>
<td></td>
</tr>
<tr>
<td>'IAPAR-Akytá'</td>
<td>8 ≤ T° &lt; 13</td>
<td>22 ≤ T° ≤ 31</td>
<td>35 ≤ T° ≤ 39</td>
<td></td>
</tr>
<tr>
<td>'Campeão-1'</td>
<td>8 ≤ T° &lt; 13</td>
<td>22 ≤ T° ≤ 31</td>
<td>35 ≤ T° ≤ 39</td>
<td></td>
</tr>
<tr>
<td>'Aporé'</td>
<td>8 ≤ T° &lt; 13</td>
<td>22 ≤ T° ≤ 31</td>
<td>35 ≤ T° ≤ 39</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Parameters M, k, z, and c, describing the germination time courses for P. vulgaris cultivars fitted by Weibull function at different constant temperatures (12.5°C, 16°C; 18°C; and 22°C).

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>M</th>
<th>k</th>
<th>z</th>
<th>M</th>
<th>k</th>
<th>z</th>
<th>M</th>
<th>k</th>
<th>z</th>
<th>12.5</th>
<th>16</th>
<th>18</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>'IAC-Carioca 80SH RC'</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.13</td>
<td>110.98</td>
<td>170.81</td>
<td>198210.61</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>'IAPAR-57'</td>
<td>12.5</td>
<td>5.2</td>
<td>0.01</td>
<td>1.6</td>
<td>0.0018</td>
<td>0.6</td>
<td>0.0018</td>
<td>0.5</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>'Aporé'</td>
<td>90</td>
<td>2.56</td>
<td>0.015</td>
<td>0.6</td>
<td>0.0018</td>
<td>0.6</td>
<td>0.0018</td>
<td>0.8</td>
<td>0.2</td>
<td>0.01</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>'Campeão-1'</td>
<td>9.5</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>1011</td>
<td>1.6</td>
<td>0.0118</td>
<td>0.6</td>
<td>0.0118</td>
<td>0.5</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>'IAPAR-57'</td>
<td>100</td>
<td>6.53</td>
<td>0.015</td>
<td>2.15</td>
<td>0.0013</td>
<td>0.24</td>
<td>198180.54</td>
<td>0.9</td>
<td>0</td>
<td>0</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>'Rosinha G2'</td>
<td>2.8</td>
<td>0.5</td>
<td>0.01</td>
<td>5.9</td>
<td>0.0120</td>
<td>0.8</td>
<td>0.0120</td>
<td>0.8</td>
<td>0.5</td>
<td>0.01</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>'Rudá'</td>
<td>9.1</td>
<td>6.8</td>
<td>1</td>
<td>0.01</td>
<td>14.89</td>
<td>1.40</td>
<td>15.50</td>
<td>1.01</td>
<td>0.1</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The cultivars responded to temperature in a similar pattern for all these parameters. All synchronization indexes (U) of frequencies’ distribution of isothermal germination (Table 3) are positive, indicating that there is a germination times scatter in the temperature treatments (Labouriau and Osborn, 1984). Generally speaking, no significant differences were found amongst U-values from 12.5 to 27°C, showing that germination is evenly scattered in the lines of Phaseolus vulgaris tested here.
Table 3. Synchronization indexes of the frequencies’ distribution of *Phaseolus vulgaris* isothermal germination. Data in bits ± confidence interval (see Material and methods for details).

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>125</th>
<th>159</th>
<th>180</th>
<th>219</th>
<th>270</th>
</tr>
</thead>
<tbody>
<tr>
<td>'IAC-Carioca-Akytã'</td>
<td>2.26 ± 0.23</td>
<td>0.84 ± 0.36</td>
<td>0.96 ± 0.43</td>
<td>1.32 ± 0.30</td>
<td>1.32 ± 0.45</td>
</tr>
<tr>
<td>'Aporé'</td>
<td>1.22 ± 0.43</td>
<td>1.20 ± 0.45</td>
<td>1.41 ± 0.14</td>
<td>1.38 ± 0.54</td>
<td>1.64 ± 0.34</td>
</tr>
<tr>
<td>'Campeão-1'</td>
<td>1.87 ± 0.44</td>
<td>1.23 ± 0.51</td>
<td>2.02 ± 0.17</td>
<td>1.62 ± 0.28</td>
<td>1.73 ± 0.41</td>
</tr>
<tr>
<td>'IAPAR-57' PP</td>
<td>0</td>
<td>0</td>
<td>1.41 ± 0.14</td>
<td>1.38 ± 0.54</td>
<td>1.64 ± 0.34</td>
</tr>
<tr>
<td>'IAPAR-57' RC</td>
<td>0</td>
<td>0</td>
<td>1.08 ± 0.36</td>
<td>1.44 ± 0.61</td>
<td>1.64 ± 0.34</td>
</tr>
<tr>
<td>Guarumbé</td>
<td>2.23 ± 0.52</td>
<td>2.04 ± 0.48</td>
<td>2.19 ± 0.16</td>
<td>1.69 ± 0.44</td>
<td>1.57 ± 0.42</td>
</tr>
<tr>
<td>'Iratim'</td>
<td>0</td>
<td>0</td>
<td>1.84 ± 0.35</td>
<td>1.15 ± 0.67</td>
<td>1.25 ± 0.31</td>
</tr>
<tr>
<td>'Iratim'</td>
<td>1.18 ± 0.66</td>
<td>0.82 ± 0.17</td>
<td>0.87 ± 0.45</td>
<td>0.52 ± 0.10</td>
<td>0.53 ± 0.28</td>
</tr>
<tr>
<td>'Rosinha G2'</td>
<td>1.72 ± 0.17</td>
<td>1.05 ± 0.25</td>
<td>1.06 ± 0.44</td>
<td>1.30 ± 0.19</td>
<td>1.67 ± 0.23</td>
</tr>
<tr>
<td>'Rudá'</td>
<td>0</td>
<td>0</td>
<td>0.87 ± 0.45</td>
<td>0.52 ± 0.10</td>
<td>0.53 ± 0.28</td>
</tr>
<tr>
<td>'Vermelho-2157'</td>
<td>0</td>
<td>0</td>
<td>0.96 ± 0.23</td>
<td>0.96 ± 0.23</td>
<td>0.97 ± 0.27</td>
</tr>
</tbody>
</table>

From cumulative germination curves fitted to Weibull function, the time to germination (GR) of the t to t percentiles were calculated for the different temperatures and plotted against temperature (T), as exemplified for cultivars 'IAC Carioca-80SH', both from Rio Claro (Figure 2A and B) and Presidente Prudente (Figure 2C and D). In Figure 2B and 2D, regression lines of GR on T were constrained to a common value of base temperature, calculated as described in M and M.

It was already observed in this paper that linear regressions describe fittingly the relationship between GR and infra-optimal temperatures on the germination of common bean cultivars, as showed by the respective correlation coefficients (Table 4). Usually, Tb values were relatively closed for each percentile although the linear regressions of Tb on percentile (Figure 3) decreased (cultivars 'IAC-Carioca-80SH', 'IAPAR-57', 'Rosinha G2', 'Campeão-1' and 'Aporé'), increased (Iratim, Guarumbé, 'IAC Carioca-Akytã' and 'Rudá') or were statistically (confidence interval, p = 0.05) parallel to the abscissa ('Vermelho 2157'), with exception of the cultivar 'Campeão-1', in which the difference between the highest and the lowest values of Tb was ≅ 2°C, the base temperature varied up to 1.3°C with germination fraction. This range was small enough to allow the assumption that Tb was relatively constant throughout each population of *P. vulgaris* tested here, and that the temperature effect on germination can be described on a thermal-time approach. Similar results were obtained by Garcia-Huidobro *et al.* (1982) with *Pennisetum typhoides*, but Dumur *et al.* (1990) reported that Tb decreased as the percentile value increased in lima bean seeds.

![Figure 2](image-url)
In the field, a species with low Tb estimates seems more adapted to germinate at cooler temperatures than a species with relatively high Tb (Steinmaus et al., 2000). The different Tb values observed for the two lots of the cultivar Carioca indicate that such a parameter is strongly influenced by the seed provenance: seeds from a warmer place (Presidente Prudente) appeared to be more sensitive to low temperatures than seeds from Rio Claro. These results partially agree with the findings of Otubo et al. (1996), according to whom Phaseolus vulgaris cv. ‘Carioca’ is sensitive to low temperature (12°C), since the sensitivity appears to be dependent on the origin of the lot.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Germination rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAC-Carioca-80SH PP</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
<tr>
<td>IAPAR-57</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
<tr>
<td>Vermelho-2157</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
<tr>
<td>Iratim</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
<tr>
<td>‘Campeão-1’</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
<tr>
<td>‘IAPAR-57’</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
<tr>
<td>Guarambê</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
<tr>
<td>‘IAC-Carioca-Akytã’</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
<tr>
<td>‘Aporé’</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
<tr>
<td>‘Rudá’</td>
<td>14.5 14.0 13.5 13.0 12.5 12.0 11.5 11.0 10.5 10.0 9.5</td>
</tr>
</tbody>
</table>

When GR (the reciprocal of time taken for a particular fraction to germinate) is linearly related to temperature, whether the base temperature is the same for all seed fractions, the different time-courses of germination at different temperatures, it can be joined in a single curve by plotting germination against thermal time (Gummerson, 1986). Since the plots of the 1/tg against temperature for the different common bean cultivars tested in this work produced acceptably straight lines (Figure 2; Table 4), the thermal time approach was used to analyse them.

A linear relationship between temperature and 50% germination rate was observed in several vegetable species, including Phaseolus vulgaris (Bierhuizen and Wagenvoort, 1974), suggesting that it is a common feature in this species. In Figure 4, the mean values of Tb were ordered from lower to higher values, showing that they ranged from ≅ 6.5°C (cultivar Rosinha G2) to ≅ 13.5°C (IAC-Carioca-80SH PP). However, with exception of these “extreme” values, the base temperatures did not vary so much among different cultivars, ranging around 8.5°C.

For all the cultivars, the amount of accumulated thermal time increases with percentile, and the germination progress curves exhibit an apparent sigmoid pattern (Figure 5), similar to the results of Covell et al. (1986) for Cicer arietinum, Lens culinaris, Glycine max and Vigna unguiculata.

In order to compare the rate of increase of thermal time to achieve germination, the relationship between thermal time and percentile was assumed to be linear, and the slope of the regression of thermal time on percentage fraction

![Figure 4](image-url)
was taken for each cultivar. The lowest increase rate (lowest slope) was observed for cultivar 'IAC Carioca-Akyta', whereas the highest rate increase occurred for cultivar 'Campeão-1'. The rest of them could be put in decreasing order, as follows: 2) 'Rudá' and 'IAPAR-57'; 3) 'IAC-Carioca 80SH' PP; 4) 'Vermelho 2157'; 5) 'IAC-Carioca 80SH' RC and Guarumbé; and 6) Iratim, 'Aporé' and 'Rosinha G2'. Taking into account that, the lower the slope, the lower the amount of thermal time required for an increment of germination, the rate of progress toward germination per unit of thermal time is higher for the cultivar 'IAC Carioca-Akyta'.

The standardized normal distribution of thermal time (°C.day) at several temperatures for different cultivars of P. vulgaris and their linear equations and correlation coefficients: 'IAC Carioca 80SH' PP (y = 11,06x - 100,44 \( R^2 = 0,98 \)); 'IAPAR-57' (y = 13,46x - 178,32 \( R^2 = 0,96 \)); 'Vermelho 2157' (y = 9,96x - 153,75 \( R^2 = 0,97 \)); Iratim (y = 6,96x - 119,23 \( R^2 = 0,96 \)); 'IAC-Carioca 80SH' PP (y = 13,46x - 178,32 \( R^2 = 0,97 \)); 'Guarumbé' (y = 7,55x - 151,41 \( R^2 = 0,96 \)); 'IAC Carioca-Akyta' (y = 30,26x - 437,43 \( R^2 = 0,97 \)).

Figure 5. Relation between cumulative germination (G%) and thermal time (°C.day) at several temperatures for different cultivars of P. vulgaris:

- 'IAC Carioca 80SH' PP
- 'IAPAR 57'
- 'Vermelho 2157'
- 'IAC-Carioca 80SH' RC
- 'Guarumbé'
- 'IAPAR-57'
- 'IAC Carioca Akyta'
- 'Rudá'
- 'Aporé'
- 'Iratim'

The lines exhibit relatively few differences regarding germination rate at the infra-optimum range of temperature, but the response to temperature can be influenced by the provenance of the seed lot, suggesting that estimates of germination response should be derived for locally adapted ecotypes, rather than extended to all members of a species.

The thermal time model could describe, relatively well, the time-course of the cultivars isothermal germination, which differed regarding the amount of thermal time requirement to germination. The cultivar 'IAC Carioca-Akyta' needs fewer degrees per day to achieve germination than others, whereas the cultivar 'Campeão-1' requires more thermal time.

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References

Figure 6. Fitted and observed isothermal germination curves for different cultivars of *P. vulgaris* on a thermal time scale. The fitted lines were $y = 5 + 1/\sigma\cdot(x - \mu)$ with parameters $\sigma$ and $\mu$: $\sigma = 0.1162, \mu = 1.1198$ (A); 0.0777, 1.3019 (B); 0.0684, 1.357 (C); 0.0825, 1.4241 (D); 0.0558, 1.2877 (E); 0.0716, 1.3128 (F); 0.0635, 1.228 (G); 0.0726, 1.4239 (H); 0.0465, 1.1786 (I); 0.0975, 1.3495 (J); 0.1326, 1.4144 (K).

Symbols: 12.5°C (○); 16°C (●); 18°C (Δ); and 22°C (◊).


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