

Effects of temperature regimes on seed germination and early growth of different soybean cultivars

Naheeda Begum^{a1}, Ling Wang¹, Tuanjie Zhao^{a1*}

¹National Center for Soybean Improvement, Key Laboratory of Biology and Genetics and Breeding for Soybean, Ministry of Agriculture, State Key Laboratory for Crop Genetics and Germplasm Enhancement, Nanjing Agricultural University, Nanjing 210095, China

Abstract

High temperature is an important global issue that impedes agricultural production, especially of soybean (*Glycine max* [L.] Merr.) crop. Numerous studies were undertaken to estimate the effect of temperature on soybean seed germination under low temperatures. However, the effects of high-temperatures on seed germination and early seedling establishment of various soybean cultivars need to be explored further. Therefore, the current study was performed in growth chambers to evaluate genetic variations among different soybean cultivars for germination and early growth under varying temperatures. Five temperatures, i.e., 15, 20, 25, 30, and 35 °C, and four soybean cultivars (PI408105A, PI567731, PI567690, and PI416937) were used. The results showed that soybean cultivars revealed substantial variations in germination percentage (GP), germination rate index (GRI), germination energy (GE), seed vigor index (SVI), and seedling length under different temperatures mentioned above. The results indicated that higher temperature [35 °C] inhibited seed germination. Conversely, the intermediate temperatures [20, 25, and 30 °C] depicted good germination. Lower temperature declined the seed germination to some extent, and the germination percentage of PI408105A, PI567731, PI567690, and PI416937 were observed as 63.33%, 56.67%, 50%, and 40.11%, respectively. For all the soybean cultivars, the mean seed germination rate was maximum at 25 °C. However, the germination rate index continued to increase until 30 °C. The soybean cultivar PI408105A was the most promising under high temperature, exhibiting higher GP by 86.67%, highest SVI by 50.95%, and GRI by 50% at 30 °C. In contrast, PI416937 was among the cultivars sensitive to high temperature and showed a higher germination rate only at 20 °C. The seeds of PI408105A, PI567731, and PI567690 can germinate well under intermediate temperature conditions, making them a promising species for use in hot climatic zones. According to the current findings, it was concluded that soybean should be planted under mild temperatures for good crop stand and production. Moreover, it is recommended that cultivars such as PI408105A could be grown in warm conditions.

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Introduction

Glycine max (L.) Merr. (Soybean) is an important legume crop, widely adapted and cultivated worldwide for its high protein content, food oil, and fatty acids. It is grown on more than 121.5 million hectares of land in all climate zones of the world (FAO, 2017). Several research studies have documented that soybean is the world's greatest protein source and the second-largest source of oil (Zener et al.,

*CONTACT Tuanjie Zhaoa, tjzhao@njau.edu.cn, National Center for Soybean Improvement, Key Laboratory of Biology and Genetics and Breeding for Soybean, Ministry of Agriculture, State Key Laboratory for Crop Genetics and Germplasm Enhancement, Nanjing Agricultural University, Nanjing 210095, China

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2014; Xu et al., 2015). Soybean is naturally capable of fixing atmospheric nitrogen; It plays an important role in contributing to soil fertility. Furthermore, some legume roots secrete special exudates capable of solubilizing phosphorus and other insoluble calcium-bound phosphorus compounds, which are considered beneficial for crop production (Lupwayi et al., 2010). Moreover, legumes promote microbial activity, particularly in the soil's rhizosphere, and contribute to organic matter renewal, thereby improving soil quality. Besides, it also plays a fundamental role in pest control and other disease prevention (Tairo, 2013). In addition to this, its remarkable adaptability to climate change, soybean has served as a model crop for C₃ annual plants. For example, a 1 °C increase in temperature has been shown to result in a 17 percent drop in yield (Komatsu and Ahsan, 2009). Several abiotic variables, such as temperature, flooding, drought, salt, and acidity significantly affect overall soybean output (Gall et al., 2015). Because of the various developmental stages of soybean, these abiotic factors have a significant impact on its growth. Therefore, crop yields must be protected from increasing and more frequent abiotic stresses, particularly exceptionally high temperatures in both current and future climates.

Temperature stress causes dehydration in cells and impacts a variety of metabolic activities in plants. Temperature stress is one of the most damaging effects in the soybean crop, resulting in dehydration of plants, disruption of potential water gradients, loss of turgor pressure, protein denaturation, and a lack of cellular membranes (Liu et al., 2017). During the germination stage of soybean plants, high temperatures can be encountered in several southern states. Temperatures above 30 °C reduce soybean seed vitality, which ultimately reduces germination. As a result, the amounts of stachyose and phytic acid in soybean seeds decreased, making the process of membrane biogenesis and germination more difficult to achieve (Ren et al., 1999). Additionally, high temperatures can also cause seed desiccation and aberrant exine structure during microsporogenesis, leading to pollen deformity (Carrera and Dardanelli, 2017). Previous studies have shown that temperature stress lowered the germination rate and vitality of growing soybean seeds (Spears et al., 1997). Soybean production is threatened by biotic and abiotic stresses, making it difficult to feed the world's growing population and meet other industrial demands. For example, each degree Celsius increase in temperature was predicted to reduce global crop yield by 6% (Asseng et al., 2015).

Consequently, identification of soybean cultivars able to establish well under high-temperature conditions may greatly influence global soybean production. The germination of seeds and the establishment of seedlings impact crop production (Hopper et al., 1979; Sharma et al., 2014). Though in plant development, the most critical stage is the germination stage, which can ominously impact the establishment and nutrient uptake of plants (Marschner, 1998).

Seedling establishment usually involves many physiological processes influenced by various environmental factors including primarily temperature, light, moisture content, availability of nutrients, etc. (Garcia-Huidobro et al., 1982). Different cultivars of different crops may have varying root lengths, lateral roots, and root dispersion during seedling establishment, affecting their water availability and ability to endure a stress during the cropping season (Matsui and Singh, 2003). The seed vigor index (SVI) is used to get a broad view of a seedling's development, which involves seed germination and seedling growth. Crops and cultivars with a maximum SVI may fast and uniformly emerge under various environmental situations (Orchard, 1977). Those crops which establish quickly have a benefit in the competition for resources.

Moreover, to understand better that how seed emerges quickly, the germination rate index and time are typically used in a seedling establishment (Wardle et al., 1991; Ranal and De Santana, 2006). Temperature is the most important ecological element impacting plant germination and early growth (Gladish and Rost, 1993; Kamkar et al., 2012) as well as crop species adaption outside of their native range.

Soybean is a thermophilic plant that requires a soil temperature above 10 °C for germination—the optimal temperature being 25 °C. Ray et al. (2015) found that some soybeans exhibited about 77% germination before being exposed to high temperatures. The germination was recorded to decline when treated with high temperature levels. The adaptation of soybean germplasm to varied environmental circumstances in Vietnam was discussed by Nguyen et al. (2021). This shows that there is a wide range of soybean cultivars growing around the world. However, little attention has been paid to soybean production, focusing primarily on different cultivars' germination stages and their early growth under various temperature treatments. Since soybean is an essential component of global food security utilized by human beings and animals, and an important component for the production of feed protein and cooking oil. Therefore, assessing different soybean cultivars for differences in germination and early growth will support soybean productivity in warm regions, which in turn will encourage soybean cultivation in other countries with related agro-climatic conditions. Thus, the present study was undertaken to assess the effects of different temperature regimes on germination and early growth of various soybean cultivars.

Materials and Methods

Experimental design and description

The seeds of respective soybean accessions were obtained from the National Center for Soybean Improvement, Nanjing Agricultural University, Nanjing-China. These accessions were planted in 2018 and 2019 at Jiangpu Experimental Station (latitude 32.12°N; longitude 118.37°E) of Nanjing Agricultural University in Nanjing, Jiangsu Province of People's Republic of China. Afterwards, the seeds were allowed to dry naturally before being cleaned and placed in a tightly sealed glass container, which was then kept at 4 °C in a refrigerator until needed for experimentations. Germination and early growth analyses of four different available soybean cultivars (PI408105A, PI567731, PI567690, and PI416937) were conducted in a growth chamber located at the College of Agriculture, Nanjing Agriculture University, Nanjing, China, with a 16 h light/8 h dark day/night pattern at five different temperatures of 15, 20, 25, 30 and 35 °C. Mature seeds were sterilized for 5 minutes in a NaOCl solution before rinsing them with distilled water (Rong et al., 2015). For each treatment, 30 healthy seeds from each cultivar were placed in each of Petri dishes (9 cm length diameter) with two layers of filter paper (1001-090, Whatman) wetted with distilled water. There were three replications for each cultivar. Germinated seeds were removed after counting to avoid inaccuracies in germination records.

Seed germination calculation

Seed germination was tracked daily during the first five days of the experiment. When the radicle length was more than 2 mm, seeds were considered germinated (Saleem et al., 2019). From the number of germinated seeds, germination percentage (GP) was on the last day to a total number of seeds planted (ISTA, 2015). Germination energy (GE) was calculated by using the below-given formula:

$$(GE, \%) = \frac{\text{No. of germinated seeds within 3 days}}{\text{total no. of seeds planted}} \times 100$$

The germination index (GI) was computed using the following Eq:

$$\text{Germination index (GI)} = \frac{\sum Gt}{Dt}$$

In the formula, number of seeds germinated on a given day is represented by Gt, and Dt represents the number of days from the start of the experiment.

The seed vigor index (SVI) was determined using the below given Eq, as described by Orchard (1977):

$$\text{Seed vigor index (SVI)} = SL \times GP$$

Where SL represents the length of the seedling and GP represents the germination percentage.

Evaluation of seedling development

The length of the seedlings was measured with a centimeter-graduated ruler at the end of the germination test. The results were expressed as cm seedling⁻¹ (Nakagawa, 1999). The experimental design was a completely randomized, with five temperature regimes using three replications. The data were analyzed by an approach of analysis of variance.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using the Statistix 8.1 software. Means were compared using the least significant difference (LSD) test at the 0.05 probability level. For data processing and plotting figures, the Sigma plot software was used. Then, Canoco 5 software was used for the principal component (PCA) analyses to discriminate the differences among different cultivars based on different treatments.

Results

Germination percentage and germination rate index performances under different temperature regimes

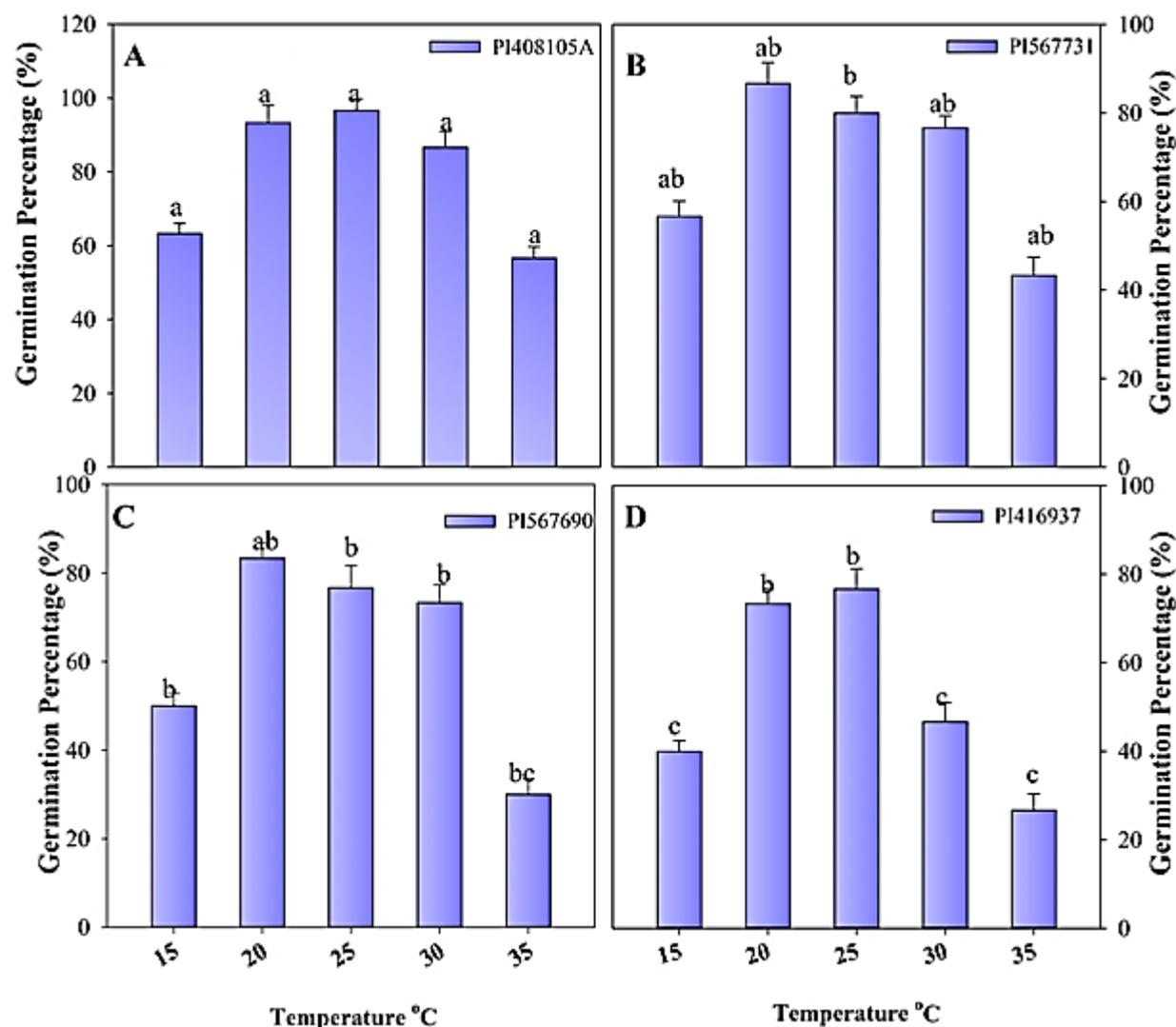
The present results demonstrated that soybean seed germination was significantly affected by different temperatures (**Figure 1**). Analysis of variance comparing the temperatures showed that the highest mean germination percentage (GP) was obtained at a temperature of 20 and 25 °C (**Figure 1**), by

Table 1. Details of soybean cultivars used in the study.

Accession number	Common name of cultivar	Origin/Country
PI408105A	KAS 633-19	Korea, South
PI567731	Fu yang (56)	China
PI567690	Fu yang (7)	China
PI416937	Houjaku Kuwazu	Japan

Table 2. Effect of different temperatures on rate of germination index (day^{-1}) of four soybean cultivars. Each data value is mean of three replicates, and different letters indicate significant differences at $P \leq 0.05$ (mean \pm SE; $n = 3$).

Cultivars	Temperature regimes				
	15 (°C)	20 (°C)	25 (°C)	30 (°C)	35 (°C)
PI408105A	4.74 \pm 0.16 a	8.14 \pm 0.31 a	8.74 \pm 0.88 a	9.48 \pm 0.16 a	5.69 \pm 0.36 a
PI567731	3.97 \pm 0.22 ab	7.46 \pm 0.29 a	8.14 \pm 0.45 a	8.51 \pm 0.57 ab	4.42 \pm 0.96 ab
PI567690	3.33 \pm 1.10 ab	7.42 \pm 0.47 a	7.98 \pm 0.17 a	7.02 \pm 1.30 b	3.04 \pm 0.60 bc
PI416937	3.11 \pm 0.59b	4.88 \pm 0.55 b	4.36 \pm 0.43 b	2.94 \pm 0.35 c	1.36 \pm 0.22 c

**Figure 1. Effect of different temperature regimes on seed germination percentages of four soybean cultivars. Each data value is mean of three replicates, and different letters indicate significant differences at $P \leq 0.05$ (mean \pm SE; $n = 3$).**

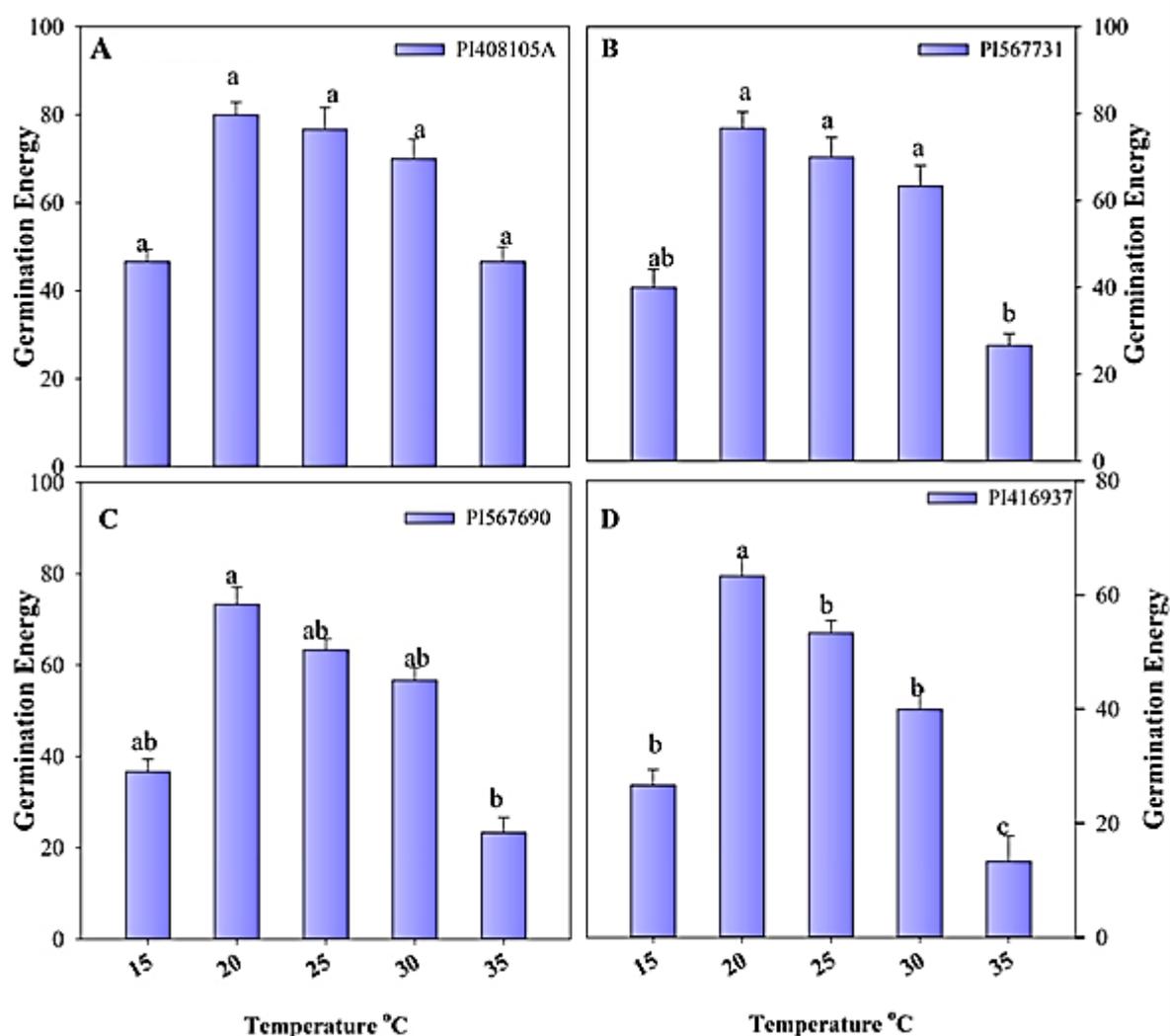


Figure 2. Effect of different temperature regimes on germination energy of four soybean cultivars. Each data value is mean of three replicates, and different letters indicate significant differences at $P \leq 0.05$ (mean \pm SE; $n = 3$).

93.33% and 96.67%. In comparison, higher temperature of 35 °C decreased the germination percentage. Lowering the temperature had a little effect on the overall GP till temperatures reached below 20 °C, while the germination was severely reduced at 15 °C. The results show that cultivar PI408105A seeds exposed at intermediate temperatures of 20, 25, and 30 °C displayed a high GP, which varied between 93.33% and 96.67% and 86.67%, respectively. The current findings revealed that higher seed germination could be achieved at temperature ranges from 20–30 °C. At average temperatures, the highest (96.67 %) germination percentage was noted in PI408105A, and the lowest (46.66 %) was observed in PI416937 (**Figure 1**). The other two cultivars (PI567731 and PI567690) had germination percentages ranging from 50% to 86.7%, respectively. The interaction occurred primarily due to the good performance of PI408105A under higher temperatures over other cultivars. Accession PI408105A achieved a maximal GP of 86.67 at 30 °C and maintained that germination rate at all other temperature regimes, except at 35 °C.

On the other hand, other soybean cultivars required lower temperatures ranging from 20 °C (e.g., PI567731) to 25 °C (e.g., PI567690 and PI416937) to attain the highest GP. In the same way as in the case of germination percentage, temperature also affected the germination rate index (**Table 1**). The results revealed that the highest rate of germination index was found at 20 and 25 °C. In comparison, the lowest rate of germination index was found at 15 °C (**Table 2**). Accession PI408105A had the highest rate of germination index among all varieties tested, followed by the PI567731 and PI567690. Accession PI416937 had the lowest rate of germination index. It is worth mentioning that the rate of germination index decreased in all varieties with an increase or decrease in temperature regime (e.g., 15 °C and 35 °C).

Table 3. Effect of different temperatures on the seedling length (cm) of four soybean cultivars. Data presented are means of each of three replicates, and different letters indicate significant differences at $P \leq 0.05$ (mean \pm SE; $n = 3$).

Cultivars	Temperature regimes				
	15 (°C)	20 (°C)	25 (°C)	30 (°C)	35 (°C)
PI408105A	4.67 \pm 0.18 a	12.00 \pm 0.37 a	10.43 \pm 0.32 a	6.07 \pm 0.29 a	1.60 \pm 0.30 a
PI567731	2.30 \pm 0.25 b	9.47 \pm 0.31 b	8.30 \pm 0.15 b	5.27 \pm 0.13 b	0.73 \pm 0.22 b
PI567690	1.73 \pm 0.07 c	8.73 \pm 0.17 b	7.40 \pm 0.09 c	4.03 \pm 0.25 c	0.83 \pm 0.14 b
PI416937	1.17 \pm 0.77 d	7.33 \pm 0.29 c	6.27 \pm 0.24 d	3.33 \pm 0.19 d	0.60 \pm 0.28 b

Table 4. Effect of different temperatures on seed vigor index (SVI) of four soybean cultivars. Each data value is mean of three replicates, and different letters indicate significant differences at $P \leq 0.05$ (mean \pm SE; $n = 3$).

Cultivars	Temperature regimes				
	15 (°C)	20 (°C)	25 (°C)	30 (°C)	35 (°C)
PI408105A	257.7 \pm 14.8 a	1120.0 \pm 36.0 a	1006.1 \pm 8.7 a	525.3 \pm 15.6 a	91.0 \pm 9.5 a
PI567731	138.3 \pm 11.7 b	818.0 \pm 10.0 b	663.7 \pm 45.5 b	404.4 \pm 14.6 b	45.1 \pm 4.5 b
PI567690	102.3 \pm 17.3 bc	728.1 \pm 32.0 b	566.1 \pm 17.1 bc	295.4 \pm 11.6 c	35.3 \pm 9.8 b
PI416937	60.0 \pm 15.1 c	567.3 \pm 29.5 c	481.2 \pm 27.1 c	156.3 \pm 16.2 d	22.9 \pm 5.6 b

Table 5. Effect of different temperatures on fresh weight (g) of four soybean cultivars. Each data value is mean of three replicates, and different letters indicate significant differences at $P \leq 0.05$ (mean \pm SE; $n = 3$).

Cultivars	Temperature				
	15 (°C)	20 (°C)	25 (°C)	30 (°C)	35 (°C)
PI408105A	1.83 \pm 0.14 a	3.63 \pm 0.27 a	3.39 \pm 0.22 a	2.87 \pm 0.29 a	2.03 \pm 0.20 a
I567731	1.32 \pm 0.22 b	3.16 \pm 0.21 ab	2.75 \pm 0.10 b	2.42 \pm 0.13 ab	1.32 \pm 0.12 b
PI567690	1.10 \pm 0.09 bc	3.09 \pm 0.17 ab	2.74 \pm 0.07 b	2.20 \pm 0.25 bc	1.14 \pm 0.14 b
PI416937	0.99 \pm 0.17 c	2.89 \pm 0.26 b	2.43 \pm 0.21 b	1.77 \pm 0.19 c	0.67 \pm 0.23 c

Germination energy under different temperatures

Germination energy of all cultivars was affected noticeably by different temperature regimes, as PI408105A showed higher germination energy than the others cultivars at the same temperature regimes (Figure 2). The present results showed a decrease in germination energy in all cultivars due to temperature increment. Germination energy of both cultivars significantly decreased when they were subjected to 35 °C, but no significant changes were observed at 20 °C and 25 °C. Accelerations of germination energy were clear in PI408105A when compared with PI416937. The results showed that the highest germination energy (Figure 2) was observed for PI408105A, and the lowest germination energy was observed in PI416937 at all temperature regimes. These results confirmed that the degree of reduction was not the same for all soybean genotypes under the temperature regimes used.

Seedling length under different temperatures

Temperature regimes significantly impacted the seedling length (SL) of the soybean cultivars (Table 3). The longest seedling length ranging from (12-6.27 cm) was noted at 20 and 25 °C, while the shortest seedling length ranging from (4.067-0.60 cm) was noted at 15 and 35 °C, respectively. Accession PI408105A produced the longest SL at the temperature range between 20–25 °C (Table 3). No significant differences for seedling length were found among the PI567731, PI567690, and PI416937. This indicates that PI408105A had a good seedling growth among the other soybean cultivars studied, while PI416937 had poor seedling growth. The seedling length of PI567731 and PI567690 were significantly increased when the temperature increased from 15 °C (Table 3).

On the other hand, compared to other cultivars, the seedling length of PI408105A was considerably increased when the temperature rose above 25 °C. Furthermore, cv. PI416937 showed the slowest increase in seedling length when the temperature was increased from 20 to 35 °C. The lower temperature drastically decreased the seedling length in almost all cultivars, but as the temperature was elevated, vigorous seedling growth started thereby producing the highest seedling length.

Seed vigor index of soybean at different temperature regimes

The seed vigor index (SVI) was increased with an increase in temperature regimes of 20 and 25 °C (Table 4). The SVI was higher at 20 °C, which was 5 times higher than that at 15 °C. Like seedling length, SVI indicates that soybean growth increases with an increase in temperature. On different levels of temperatures, the SVI of all cultivars significantly differed. The results showed that PI408105A displayed the maximum (525.33 \pm 15.6) SVI among the cultivars, although PI416937 showed the lowest (156.33 \pm 16.2) SVI at 30 °C (Table 4). These results confirmed that at a higher temperature regime, the cultivar

PI408105A had the higher SVI among soybean cultivars used in this study. Cultivar PI408105A showed a maximum (1120.0 ± 36 and 1006.1 ± 8.7) SVI at the intermediate temperature range (20–25 °C). The maximum SVI for each cultivar was documented at 20 or 25 °C. Accession PI416937 had the lowest (60.00 ± 15.1) SVI at 15 °C, but as the temperature rose, the SVI of PI416937 increased by 567.3 ± 29.5 and 481.2 ± 27.1 at the temperature range of (20–25 °C). At 25 °C, the SVI was similar in PI567731 and PI567690. Remarkably, accession PI408105A had a more stable SVI than those of other cultivars when the temperature rose from 20 to 30 °C.

Shoot fresh weight under different temperature conditions

The soybean cultivars' shoot fresh weights affected by different temperatures are presented in **Table 5**. The present results exhibited that the fresh shoot weight of different cultivars of soybean was considerably different. The results indicated that the maximum shoot fresh weight was noted at 20 and 25 °C in the soybean cultivars PI408105A, PI567731, and PI567690, respectively, While the minimum average shoot weights (were noted in cv. PI416937 at the same temperature regimes. In addition, at higher temperatures, the maximum values such as (2.87 and 2.01 g) of fresh shoot weight were recorded in cultivar PI408105A at both 30 and 35 °C temperature regimes, respectively (**Table 5**).

Multivariate statistical analysis

Principal component analysis (PCA) was performed to detect the germination and early growth response patterns in soybean cultivars under different temperature regimes (**Figure 3**). In the temperature treatment, the results of the principal component analysis accounted for 47.11% of all variables, with the first axis elucidating 96.67% of the variation and the second demonstrating 2.52% (**Figure 3**), respectively; further, the results demonstrated the apparent differences among treatments and parameters. Germination percentage, germination energy, germination rate index, seedling length, seed vigor index, and fresh weight were positively correlated with temperature, as evidenced by the PCA. Overall, no species exhibited both low and high-temperature resistance completely. However, cultivar PI408105A exhibited a higher germination rate, germination energy, seed vigor index, and improved early growth at high temperatures, which is suitable for warm regions, while PI416937 was least adaptive among all the cultivars and showed both relatively poor low and high temperature-resistance, compared to the other cultivars.

Discussion

The ability of cultivated plants to establish themselves is largely determined by how quickly and uniformly they germinate (Bidgolya et al., 2018; Fakhfakh et al., 2018). The appropriate water availability and temperature conditions for germination are only available for a limited time in most arid and semi-arid environments (Watt and Bloomberg, 2012; Belo et al., 2014; Fakhfakh et al., 2018). The instant study presents a comprehensive report on soybean seed germination responses to various temperatures in soybean, an important economic legume crop that plays an important role in human and animal nutrition (Barker et al., 1990). The results showed that the maximum seed germination percentage (GP percentage, 96.67%) was recorded at temperatures between 20 and 30 °C. Of all soybean cultivars examined here, the cultivar PI408105A had the highest GP (93.33-96.67%), followed by cultivars PI567731 and PI567690, which had the lowest seed germination (73.33%) and the highest GP percentage (86.67%). Our findings clearly show that the temperature had a significant impact on the final germination percentage of soybeans. The temperature-dependent germination of seeds has been demonstrated in several species, including common vetch (*Vicia sativa*) (Liu, 2010), *Stipa* species (Ronnenberg et al., 2008), and *Carex* spp., a temperate sedge (Rave, 1999), as well as, in several other species. The final germination percentage for soybean was quite high (i.e., 93.33 to 96.67%) when grown at temperatures ranging from 20 to 30 °C (**Figure 1**). The seed germination and early growth of soybean plants were nearly quadrupled when the germination temperature was raised from 20 to 30 °C; these findings being consistent with previous researches (Wuebker et al., 2001). On the other hand, lower temperatures for optimum germination of soybean seeds were similar to those for wild *Allium* species found in the temperate desert steppe (Zhao et al., 2011). This response is most likely linked to seed enzyme activity and oxygen availability, both of which have been shown to decrease when seeds are germinated at unfavorable temperatures and under dry conditions (Bewley and Black, 1994). Vinisky and Ray (1985) discovered that cv. Kinman of guar (*Cyamopsis tetragonoloba*) had much higher germination than other cultivars when tested at temperatures ranging from 25 to 37 °C. Soybean crops respond differently to varying temperatures in terms of germination. At 7 °C, for example, different soybean cultivars displayed different germination rates (Sichkar et al., 1987); this was not observed in field bean cultivars when temperatures were between 10 and 30 °C (Khamassi et al., 2013).

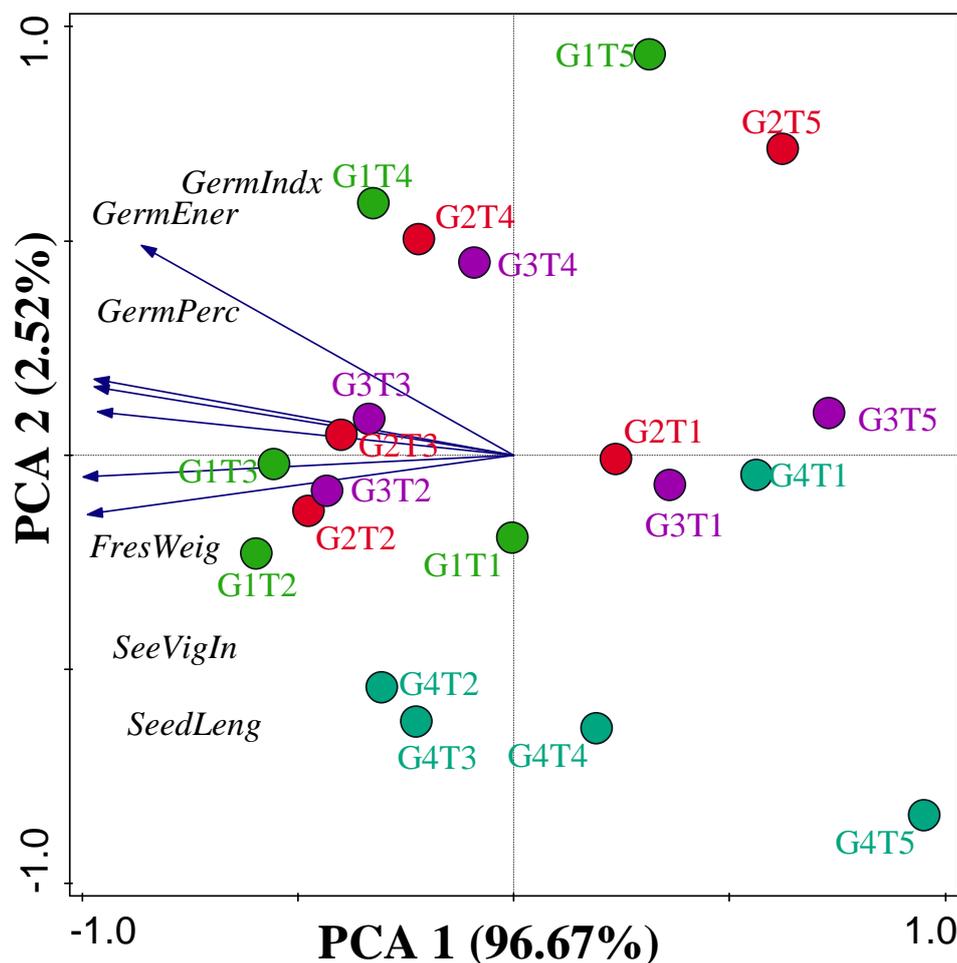


Figure 3. Multivariate statistical analysis PCA (Principal Component Analysis) of four soybean cultivars under different temperatures.

GermPerc: Germination percentage; GermEner: Germination energy; Fres weig: Fresh weight; Seevigin: Seed vigor index; Seedling Length; Germindx: Germination index; G: Genotypes; G1-G4: PI408105A, PI567731, PI567690, and PI416937; T: Temperature; T1-T5: 15, 20, 25, 30, and 35 °C.

These findings indicated that accession PI408105A is a good choice for a wide range of temperatures, particularly at higher temperatures, but PI416937 should not be planted in the hot climate. Furthermore, the temperature has a considerable impact on crop germination percentage and germination rate index. With increasing temperature, the germination rate index increased steadily (Table 2).

In this study, the effect of temperature on the germination rate index (GRI) was detected (Table 2). The GRI is a complete germination assessment that deliberates the GP and speed to accentuate differences in germination between cultivars. GRI was lower at lower temperatures and higher with increasing temperatures, with the maximum measured at 25 °C. This demonstrates that as the temperature rises, the number of soybean seeds germinating every day will increase. Our findings support those of Hu et al. (2002), who discovered that guar seeds germinate most quickly at 27 °C. The present results showed that GRI was the highest in PI408105A, followed by PI567731, PI567690, and PI416937 (Table 2). When averaged over all temperatures, PI567731 and PI567690 had similar GRI. This demonstrates that soybean cultivars do not germinate simultaneously and that there are significant variances between them. Breeders working to improve soybean germplasm could benefit from this information.

Furthermore, the highest seedling length (12 cm) was found at 20 °C, followed by 10.43 cm that at 25 °C, and minimum seedling length (0.60 cm) was observed at 35 °C and 1.73 cm at 16 °C. In terms of cultivars, cultivar PI408105A had the longest seedling length (12 cm) across all temperatures, followed by PI567690 and PI567731 (Table 3). High temperatures have a well-documented impact on the growth and development of many crops (Wang et al., 2015). Their findings support our results and explain that the ideal temperature is crucial at the seed germination and early growth stage.

Furthermore, the results revealed that the highest fresh weight (3.63, 3.16 and 3.09 g) was

observed at a temperature of 20 °C, compared to (0.98 g) at a temperature of 16 °C, while the lowest fresh weight (0.673 g) was observed at a temperature of 35 °C. In terms of cultivars, the cultivar PI408105A had the highest fresh weight, followed by cultivars PI567731 and PI567690, and cultivar PI416937 had the lowest fresh weight. The findings of this study are consistent with those of Singh et al. (2021), who found that the growth of primary root was critically reliant on temperature, with the longest and lowest seedling lengths measured at 28 and 13 °C, respectively. Enhanced root length could increase cell division at higher temperatures (López-Sáez et al., 1969). Additionally, the previous research reported that heat accumulated units were directly linked with the depth of roots in various sunflower cultivars (Angadi and Entz, 2002). Also, Stafford and McMichael (1990) found that the length of root in guar increased as the temperature rose from 20 to 35 °C.

Moreover, the instant results also showed that the seed vigor index (SVI) increased with each incremental temperature treatment (Table 4). At 25 °C, the SVI was more than five times higher than at 15 °C. SVI, like SL, suggests that as the temperature rises, soybean crop establishment improves. Other crops, such as wheat, have shown an increase in SVI with increasing soil temperature from 20 to 30 °C (Buriro et al., 2011). The SVI of different cultivars differed significantly when temperatures were averaged. Among the cultivars tested, PI408105A had the highest SVI, while PI416937 had the lowest (Table 4). The changes in SVI were due to genetic variation in germination and overall seedling length. The current results imply that accession PI408105A showed the higher SVI for speedy and constant emergence among the soybean cultivars studied. The findings corroborate with a previous study by Singh et al. (2021), who found that different guar cultivars responded to temperature differently. The accession PI408105A had a lower SVI at 13 °C, but when the temperature increased to 28 °C, it had the highest SVI numerically as compared with other cultivars. When temperatures were near 30 °C, PI408105A showed the best seedlings emergence.

Conclusion

The results from the present trial showed that soybean cultivars demonstrated substantial variations for germination and early growth under different temperature regimes. Cultivar PI408105A exhibited a higher germination rate, germination energy, seed vigor index, and improved early growth, which is thus suitable for warm regions, while cultivar PI416937 was least adaptive among all the cultivars. The identification of heat-tolerant cultivars may provide many prospects to farmers in warm regions. Further research should be carried out in future to evaluate genetic variation for heat tolerance among diverse germplasm from different parts of the world. In addition, studies are necessary to conduct more indoor and field experiments on large scales.

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