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Germination and early growth response of guar cultivars to low temperatures

Jagdeep Singh[a], Ivette Guzman[a], Sultan Begna[b], Calvin Trostle[c], Sangu Angadi[a,*]

[a] Department of Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM, 88003, USA
[b] Water Management Research, USDA-ARS, Parlier, CA, 93648, USA
[c] Texas A&M AgriLife Extension Service, Lubbock, TX, 79403, USA

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ABSTRACT

Demand for galactomannan gum from guar, commonly known as guar gum, has exponentially increased in the last few decades due to increased use in oil and natural gas, food, cosmetics, paper and other industries. The United States of America is the major importer of the guar gum in the world, which is mainly grown in deserts of India and Pakistan. There is need to increase guar production in non-traditional areas to ensure steady supply and reduce market volatility. Expanding guar acreage into cooler regions of the southern High Plains or in similar agroclimatic regions of the world is an attractive option. Therefore, a study was conducted in incubators to assess genetic variations among currently available guar cultivars for germination and early growth under cooler temperature ranges. Six temperatures (13, 16, 19, 22, 25, and 28 °C) and six guar cultivars (Kinman, Lewis, Matador, Monument, Santa Cruz and Judd 69) were used. Guar cultivars exhibited significant variations for germination percentage, mean germination time and seed vigor index under lower temperatures, which narrowed as the temperature increased closer to optimum. Mean seed germination percentage of cultivars reached maximum at 22 °C. However, speed of germination and seed vigor indices, which are indicators of quick and uniform establishment of guar in the field, continued to increase till 28 °C. Kinman, which was the most promising guar cultivar under cooler temperature, reached maximum germination percent at 16 °C and had the lowest germination time and highest seed vigor index among cultivars below 16 °C. In contrast, Matador reached maximum germination at 26 °C. Germination and early seedling traits indicate that it is better to plant guar in warm soils and if needed to plant in cooler conditions, cultivars like Kinman should be used.

1. Introduction

Guar [*Cyamopsis tetragonoloba* (L.) Taub.] is a summer annual legume crop cultivated in India, Pakistan, and USA (Morris, 2010). It is a multi-purpose crop used as a green manure, vegetable and forage, but growing the crop for grain production for industrial use is increasing world wide. As a green manure, it improves soil productivity through the addition of N into the soil (Elsheikh and Ibrahim, 1999). Guar gum, an extract from guar seed, is extensively used in mining (Crescenzi et al., 2004), hydraulic fracturing (Coveney et al., 2000) pharmaceutical and other industries (Patel et al., 2014). Guar is a drought tolerant crop with lower water requirements than many of the world's annual crops. In addition to 191 mm rainfall, 268 mm of irrigation was required for producing 2.4 Mg ha^{-1} seed when grown in the Mediterranean environment of Italy (Gresta et al., 2013). The majority of guar is produced under rainfed conditions in the deserts of India and Pakistan where it receives 300−400 mm rainfall annually (Hema Yadav, 2014). This indicates the potential of growing guar in areas where irrigation availability is non-existent or limited, and production is mainly rainfed (Bibi et al., 2014). Therefore, guar could be a great alternative crop under limited irrigation conditions in the southern High Plains (SHP) of the USA (Abidi et al., 2015).

The USA is the largest guar gum importer (62 %), while India is the largest exporting country in the world (Hema Yadhav, 2014). In 2012, the world demand for guar gum surged exponentially and the price rose 2.3 times (Gresta et al., 2013). The extent of guar gum import could be reduced by increasing the guar production area, specifically in the drier regions of the SHP, where the climatic conditions are similar to guar growing regions of India (Abidi et al., 2015). Currently, the area under guar production in the USA is less than 25,000 ha, while the potential is

* Corresponding author at: Agricultural Science Center at Clovis, 2346 State Road, New Mexico State University, Clovis, NM, 88101, USA.
E-mail address: angadis@nmsu.edu (S. Angadi).

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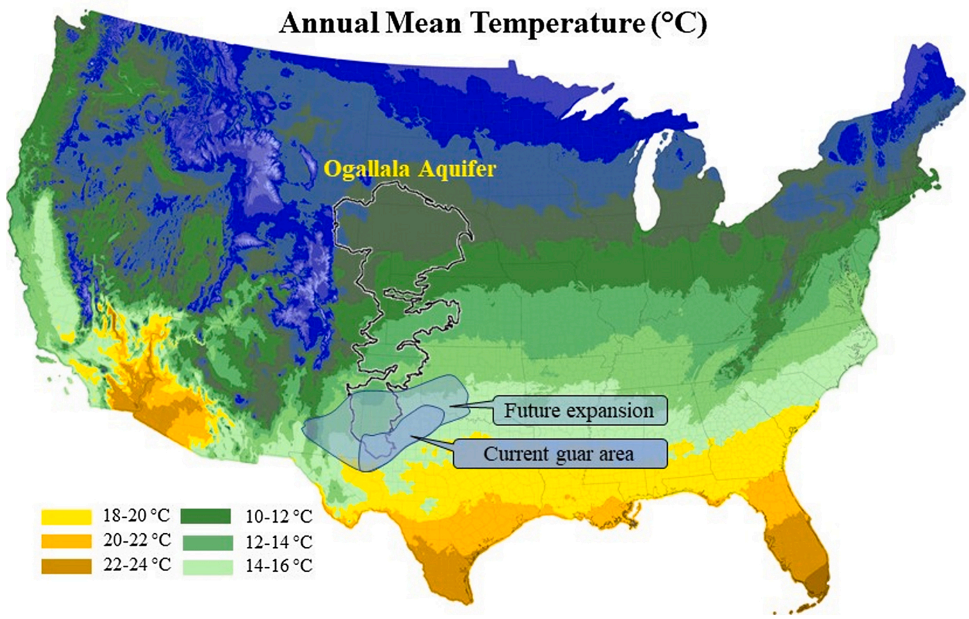

Fig. 1. Current guar acreage in the US in relation to average annual temperature (from 1981 to 2010) and potential to increase guar area if cold tolerant cultivars are developed. Annual average map was retrieved from http://prism.oregonstate.edu.

more than 100,000 ha (Trostle, 2012). Increasing the area under guar production in the USA and in similar non-traditional guar producing countries will reduce variability in the guar gum pricing. To achieve this target, planting must extend to the cooler and drier regions that are not known for growing guar but have the potential to grow it, similar to future area for guar production proposed in SHP (Fig. 1). Thus, identifying guar cultivars that can germinate and establish well in cooler soil temperature will have an impact on world guar industry. Identification of such cultivars will also open a window for farmers, who are willing to plant guar early in a cropping season.

Production of crops is influenced by seed germination and seedling establishment (Hopper et al., 1979; Sharma et al., 2014). Seedling establishment involves several physiological processes and depends on different microclimatic factors including light, temperature, moisture, and nutrient availability (Garcia-Huidobro et al., 1982). Although seed germination is one of the most critical stages in plant growth, root formation and development can significantly influence crop establishment and nutrient acquisition (Marschener, 1998). Different crops and different cultivars can have different root lengths, number of lateral roots and root distributions during seedling establishment. This defines their access to water and potential to tolerate drought stress during the cropping season (Matsui and Singh, 2003). The seed vigor index, involving both seed germination and seedling length, is used to obtain an overall picture of a developing seedling. Crops and/or cultivars having higher seed vigor index will have more uniform emergence under a range of environmental conditions (Orchard, 1977). Crop cultivars with quick establishment have an advantage in competing for resources. To better understand how fast a seed emerges, mean germination time (time required to obtain maximum germination of seeds), and speed of germination index (total number of seeds germinating in a period of time) are frequently used in crop establishment studies (Ranal and De Santana, 2006; Wardle et al., 1991).

Table 1
Details of guar cultivars used in the study.

Name of Cultivar	Year Released	Organization	References
Kinman	1975	TAES, OAES, and USDA	Stafford et al. (1976)
Santa Cruz	1984	AAES and USDA	Ray and Stafford (1985)
Lewis	1984	TAES, AAES, and USDA	Stafford and Ray (1985)
Matador	2004	TTU and HES	Abidi et al. (2015)
Monument	2004	TTU and HES	Abidi et al. (2015)
Judd 69	No official information, anecdotal evidence suggests farmers' selection and more recent origin (2010s)		

TOAES = Texas Agricultural Experiment Stations.
OAES = Oklahoma Agricultural Experiment Stations.
AAES = Arizona Agricultural Experiment Station.
TAES = Texas Agricultural Experiment Stations.
TTU = Texas Tech University.
HES = Halliburton Energy Services, Inc.

Temperature is the main environmental factor affecting germination and early crop growth (Gladish and Rost, 1993; Kamkar et al., 2012) and adaptation of crop species beyond their area of origin. Different plant species have different minimum temperatures (also known as base temperature), below which no germination will occur (Alvarado and Bradford, 2002). Guar planting is recommended when the soil temperature is at least 21 °C (Undersander et al., 1991). Gresta et al. (2018) found that some of the guar cultivars germinated at 15 °C fixed temperature and no germination was recorded below 15 °C. Guang-hua et al. (1980) did not observe any guar seeds germinating at temperatures lower than or equal to 10 °C. Rasheed et al. (2015) mentioned about the adaptability of local guar germplasm to different environmental conditions of Pakistan. This indicates that the diversity exists among the guar cultivars grown throughout the world.

Guar research, particularly on seed germination and early growth of different cultivars under varying temperature conditions, is limited. With global interest in using fracking or fracturing technology to extract oil and natural gas from shale gas reserve and guar gum being an important component of fracking process, demand for guar gum is going to increase worldwide. Therefore, assessing guar cultivars developed over the last forty-five years for variations in germination and early growth will help guar industry to grow in cooler regions of SHP, which in turn will stimulate guar cultivation in other countries with similar agro-climatic conditions. This study was carried out with the objective of assessing the effects of different temperatures on germination, early growth and root growth potential of available guar cultivars that were developed in different breeding programs in the US and identify suitable guar cultivar for planting in cooler soil temperature.

2. Materials and methods

2.1. Experimental design and description

An incubator study was conducted at the Agricultural Science Center at Clovis, New Mexico. Germination and early growth of six different available guar cultivars (Kinman, Monument, Judd 69, Matador, Lewis, and Santa Cruz) were determined at six different constant temperatures of 13, 16, 19, 22, 25 and 28 °C under dark conditions in two identical incubators (Precision Incubator, Model 818, Thermo Scientific, Grand Island, NY, USA). These temperatures were chosen to simulate the ambient environmental conditions in the SHP of USA, particularly in the cooler regions (Fig. 1). This information will be useful in other parts of the world, where cooler soil conditions are limiting guar adoption. More information on cultivars used in this study is provided in Table 1. A split plot design was employed with temperatures as the main plot and cultivars as the sub plot. All treatment combinations were replicated four times. Fifty seeds of each cultivar per replication were placed in germination pouches (18 cm × 16.5 cm, CYG Seed Germination Pouches; Mega International, USA). Seed pouches helped in visualizing root growth. Seeds were pre-treated with commercially available Clorox® bleach (Clorox Company, Oakland, California) to retard any microbial growth. Germination growth pouches were examined daily, and additional distilled water was added as required. The last reading was recorded when 50 % of seedlings reached 2.54 cm (1 inch) shoot height. The batch run for each temperature was terminated after 20 DAP if seedlings did not reach 2.54 cm shoot height.

2.2. Data collection

The germination percentage of all the cultivars was tested before starting the experiment and found satisfactory at room temperature of 25 °C. Daily seed germination count was recorded, and seed was considered germinated if there was a visible 2 mm radicle protrusion. Final seed germination percentage (FSGP) was computed as the ratio of the number of germinated seeds on the final day to the total number of seeds tested (ISTA, 2015). At the end of the trial, length of root and shoot, and number of lateral roots were recorded. As suggested by Orchard (1977) seed vigor index (SVI) was calculated by Eq. (1):

$$\mathrm{SVI} = \mathrm{SL} \times \mathrm{FSGP} \tag{1}$$

Where SL is the total seedling length in cm and FSGP is the final seed germination percentage.

Speed of germination index (SGI) was computed using Eq. (2), as recommended by Wardle et al. (1991) and Mean germination time (MGT), was estimated using the Eq. (3), developed by Ranal and Santana, (2006):

$$\mathrm{SGI} = \sum_{i=1}^{n} \frac{N_i}{T_i} \tag{2}$$

$$\mathrm{MGT} = \frac{\sum_{i=1}^{n} N_i T_i}{\sum_{i=1}^{n} N_i} \tag{3}$$

Where N_i is the number of seeds germinated on the ith day (T_i) and n is the last day of germination recorded.

2.3. Statistical analysis

Data was analyzed using PROC GLIMMIX procedure in SAS 9.4 (SAS Institute, Inc.). Temperature and cultivar were treated as fixed effects, while replication and replication x temperature were treated as random effects. The final seed germination percentage data was transformed using the box-cox method. The square root transformation was applied to the primary root length, seed vigor index, and speed of germination index data. The logarithmic transformation was used for mean germination time data. Transformations ensured normality of the data and back transformation was done for calculating the means. REML (Restricted Maximum Likelihood) method was used for calculating the variance components. The Kenward Rodger procedure for denominator degrees-of-freedom adjustment was applied for approximation of both the F statistic and its df (Kenward and Roger, 1997). Pairwise comparisons and mean separation were done using macro %Pdmix800 (Saxton, 1998). All statistical differences were performed at $P \leq 0.05$ unless otherwise stated.

3. Results and discussion

3.1. Final seed germination percentage

Final seed germination percentage (FSGP) was significantly ($P <$ 0.001) affected by temperature, cultivars, and temperature x cultivar interactions treatments. Averaged over cultivars, mean FSGP ranged from 40.1–91.1% under 13 and 22 °C, respectively (Table 2). Lowering the temperature did not change the overall FSGP significantly until temperatures were below 22 °C, at which significant reduction in germination occurred. Cultivated guar originated in sub-tropical environment and it is adopted to higher soil temperature for better seed germination. Results of the study indicates that we can get maximum germination in the temperature range between 22−28 °C.Averaged over temperatures, the highest (93.9 %) germination percentage was observed in Kinman and the lowest (72.1 %) was in Lewis (Table 2). Other four cultivars (Monument, Judd 69, Matador and Santa Cruz) had germination percentages in the range of 72.7–85.2%. Germination

Table 2
Interaction effects of temperature and cultivar on final seed germination percentage of six guar cultivars grown in a dark growth chamber at temperature range of 13−28 °C. Standard error of means are shown in parentheses.

Cultivars	Final seed germination percentage (%)						
	Temperature						
	13 (°C)	16 (°C)	19 (°C)	22 (°C)	25 (°C)	28 (°C)	Average
Kinman	77.6 (6.3) aB	98.5 (1.0) aA	98.5 (1.0) aA	97.0 (1.3) aA	95.5 (1.9) aA	95.0 (1.7) aA	93.9 (1.7) a
Monument	19.1 (1.0) cdD	45.7 (6.6) eC	85.0 (1.3) bB	93.0 (1.3) aA	91.0 (1.0) abAB	91.6 (3.0) aA	75.3 (4.9) c
Judd 69	32.1 (10.1) cC	80.0 (1.6) bB	96.5 (1.7) aA	97.5 (1.3) aA	93.5 (1.7) aA	96.0 (1.4) aA	85.2 (4.0) b
Matador	11.8 (3.6) dD	39.2 (2.9) eC	67.7 (3.4) dB	92.1 (2.2) abA	96.0 (1.8) aA	95.0 (1.7) aA	72.7 (5.5) cd
Lewis	29.8 (5.0) cC	54.9 (4.0) dB	86.5 (1.3) bA	85.1 (2.9) bcA	81.5 (0.5) cA	80.7 (3.7) bA	72.1 (3.8) d
Santa Cruz	43.9 (5.5) bD	73.1 (2.6) cC	76.0 (0.8) cBC	81.1 (2.4) bAB	85.5 (1.7) bcA	77.0 (1.3) bBC	73.7 (2.6) cd
Average	40.1 (5.4) D	67.6 (4.4) C	85.6 (2.3) B	91.1 (1.4) A	90.6 (1.2) A	89.5 (1.7) AB	

Values within a column followed by same lowercase letters are not significantly different at $p \leq 0.05$.
Values within a row followed by same uppercase letters are not significantly different at $p \leq 0.05$.

Table 3
Interaction effects of temperature and cultivar on primary root length of six guar cultivars grown in a dark growth chamber at temperature range of 13−28 °C. Standard error of means are shown in parentheses.

Cultivars	Primary root length (cm)						
	Temperature						
	13 (°C)	16 (°C)	19 (°C)	22 (°C)	25 (°C)	28 (°C)	Average
Kinman	0.8 (0.2) aE	3.2 (0.2) aD	5.9 (0.1) aC	6.2 (0.4) abBC	7.1 (0.3) aAB	8.0 (0.3) abA	4.8 (0.6) a
Monument	0.1 (0.01) cdD	0.9 (0.2) dC	5.5 (0.3) aB	6.3 (0.2) abB	7.6 (0.03) aA	8.6 (0.7) aA	3.8 (0.8) d
Judd 69	0.3 (0.1) bE	2.0 (0.1) bD	5.6 (0.1) aC	6.9 (0.5) aB	7.6 (0.3) aAB	8.0 (0.6) abA	4.3 (0.7) b
Matador	0.1 (0.02) dE	0.3 (0.03) eD	1.6 (0.1) bC	4.3 (0.5) cB	6.2 (0.3) bA	6.9 (0.2) cA	2.3 (0.6) e
Lewis	0.2 (0.1) bcD	1.3 (0.1) cC	5.4 (0.4) aB	6.2 (0.5) abA	7.2 (0.2) aA	7.5 (0.2) bcA	3.9 (0.7) cd
Santa Cruz	0.4 (0.1) bD	2.0 (0.1) bC	5.3 (0.3) aB	5.9 (0.2) bB	7.3 (0.5) aA	7.7 (0.3) abcA	4.1 (0.7) bc
Average	0.2 (0.1) F	1.4 (0.2) E	4.7 (0.4) D	5.9 (0.2) C	7.1 (0.2) B	7.8 (0.2) A	

Values within a column followed by same lowercase letters are not significantly different at $p \leq 0.05$.
Values within a row followed by same uppercase letters are not significantly different at $p \leq 0.05$.

percentage of Lewis was not statistically different from Matador and Santa Cruz. The difference in germination among the cultivars suggests that there is a potential for increasing the guar production area by planting specific guar cultivar suited for cooler soil temperature and, hence, potentially expanding the guar production area beyond its current area of production. Vinisky and Ray (1985) found significantly higher germination of Kinman compared with Lewis and Santa Cruz when tested at temperature range of 25−37 °C under 0 bars osmotic conditions. Our study focused on assessing guar cultivar germination under cooler temperature stresses. These results suggest that guar cultivars may vary in germination percentages under different stress situations. Kinman out performing many other guar cultivars is promising for expanding guar acreage in cooler environments.

The presence of temperature x cultivar interaction for germination percentage among guar cultivars developed in the last 45 years is very important for guar industry in SHP (Table 2). Even though guar developed in hot and dry environment of a desert, cultivars varied in germinating under cooler temperatures. The interaction mainly occurred because a few guar cultivars like Kinman performed very well under lower temperatures compared to other cultivars. Kinman reached peak FSGP of 98.5 % at 16 °C and continued to maintain that germination levels as the temperature increased to 28 °C. In contrast, other guar cultivars needed higher temperatures of 19 °C (e.g. Judd 69 and Lewis) to 25 °C (e.g. Santa Cruz) to reach highest FSGP. These results affect global guar industry in multiple ways. First, if farmers in cooler regions like SHP (Future expansion areas in Fig. 1) delay their planting until soils warm up to 22 or 25 °C, they may not have enough days for the crop to mature. Now, they have the option to plant Kinman when soil warms to 16 °C and do not have growing season problem. Second, presence of guar cultivars suitable for cooler environment will encourage breeding programs in SHP and in other parts of the world to develop better adopted and higher yielding cultivars for the region without worrying about temperature at planting. Interest in shale gas reserve around the world is increasing tremendously with success of fracking technology in the US. Instead of competing for finite supply of guar gum, they will be interested in developing local guar industry with well adopted cultivars. Different crops have different germination response to low temperatures. For example, soybean varieties showed differences in germination 7 °C (Sichkar et al., 1987) which was not seen in field bean cultivars under the range of temperatures of 10–30 °C (Khamassi et al., 2013). These observations suggest that Kinman is a better option over wide range of temperatures especially lower temperatures, while Matador should not be planted in cooler regions of SHP.

3.2. Primary root length

Rooting depth of guar cultivars, measured as primary root length (PRL), was highly dependent on temperature (Table 3). The longest and shortest root lengths were recorded at 28 and 13 °C, respectively. Increased cell division at higher temperatures could be the reason for increased root length (López-Sáez et al., 1969). Accumulated heat units were directly related to rooting depth in diverse sunflower cultivars under cooler field conditions (Angadi and Entz, 2002). Our finding is supported by Stafford and McMichael (1990), who reported increasing root length in guar with increasing temperature from 20 to 35 °C.The longest PRL was produced by Kinman over the temperature range of

Fig. 2. Visual presentation of guar cultivar differences for early growth at 16 °C.

Table 4
Interaction effects of temperature and cultivar on seed vigor index of six guar cultivars grown in a dark growth chamber at temperature range of 13−28 °C. Standard error of means are shown in parentheses.

Cultivars	Seed vigor index						
	Temperature						
	13 (°C)	16 (°C)	19 (°C)	22 (°C)	25 (°C)	28 (°C)	Average
Kinman	105 (6) aD	471 (27) aC	817 (23) aB	841 (50) abB	938 (44) abB	1099 (55) abA	653 (83) a
Monument	3 (0.4) cdE	67 (21) dD	696 (29) abC	832 (27) abB	974 (21) abB	1133 (116) aA	469 (111) c
Judd 69	16 (9) bE	245 (13) bD	778 (26) abC	934 (81) aB	1014 (61) aAB	1115 (93) abA	570 (107) b
Matador	1 (1) dE	18 (3) eD	171 (22) dC	598 (75) dB	883 (61) abA	983 (46) bcA	300 (87) d
Lewis	13 (4) bcD	123 (16) cC	678 (43) bcB	770 (57) bcAB	849 (42) bA	900 (51) cA	453 (91) c
Santa Cruz	30 (8) bD	230 (17) bC	578 (30) cB	680 (24) cdB	904 (54) abA	878 (30) cA	473 (80) c
Average	19 (6) F	161 (30) E	592 (54) D	772 (31) C	926 (21) B	1015 (33) A	

Values within a column followed by same lowercase letters are not significantly different at $p \leq 0.05$.
Values within a row followed by same uppercase letters are not significantly different at $p \leq 0.05$.

Table 5
Interaction effects of temperature and cultivar on mean germination time of six guar cultivars grown in a dark growth chamber at temperature range of 13−28 °C. Standard error of means are shown in parentheses.

Cultivars	Mean germination time (day)						
	Temperature						
	13 (°C)	16 (°C)	19 (°C)	22 (°C)	25 (°C)	28 (°C)	Average
Kinman	11.6 (0.5) bA	5.6 (0.3) cB	3.0 (0.1) cC	2.5 (0.1) bCD	2.1 (0.1) bDE	1.8 (0.1) bcE	3.5 (0.5) d
Monument	15.8 (0.8) aA	11.0 (0.9) aB	4.9 (0.7) aC	2.6 (0.1) bD	2.1 (0.1) bE	1.8 (0.1) cE	4.5 (0.8) b
Judd 69	12.3 (0.8) bA	7.7 (0.7) bB	3.2 (0.1) cdC	2.6 (0.1) bD	2.1 (0.1) bDE	1.9 (0.1) bcE	3.8 (0.6) c
Matador	17.0 (0.1) aA	11.7 (0.4) aB	5.5 (0.1) aC	3.4 (0.2) aD	2.8 (0.1) aE	2.3 (0.02) aF	5.4 (0.8) a
Lewis	12.4 (0.6) bA	7.6 (0.5) bB	3.9 (0.6) bcC	2.6 (0.1) bD	2.2 (0.1) aDE	2.1 (0.4) abE	4.1 (0.6) c
Santa Cruz	11.9 (0.7) bA	6.7 (0.4) bB	4.0 (0.5) bC	2.7 (0.1) bD	2.3 (0.1) aDE	2.1 (0.1) abE	4.0 (0.5) c
Average	13.3 (0.5) A	8.1 (0.5) B	4.0 (0.2) C	2.7 (0.1) D	2.3 (0.1) E	2.0 (0.1) F	

Values within a column followed by same lowercase letters are not significantly different at $p \leq 0.05$.
Values within a row followed by same uppercase letters are not significantly different at $p \leq 0.05$.

13−28 °C (Table 3). No significant differences for PRL were observed among Judd 69, Santa Cruz, Monument, Lewis. This suggests that Kinman has better seedling root growth among the guar cultivars studied, while Matador had poor root growth.

Significant interaction ($p < 0.001$) between temperature and cultivar for PRL was observed in this study. A drastic increase in root length was observed in four cultivars when temperature increased from 16 to 19 °C (Table 3). However, Kinman quickly responded to the temperature and increased PRL rapidly as the temperature raised above 13 °C. The Matador recorded the slowest increase in PRL with increasing the temperature from 16 to 19 °C. The PRL of Kinman was observed to dominate only at a lower temperature range of 13−16 °C (Fig. 2). Matador performed poorly and recorded lowest PRL from 13 to 25 °C. Monument did not perform well at lower temperatures, but as temperature increased, it started its vigorous root growth and produced numerically the highest root length at 28 °C. This indicates that Kinman roots establish faster under cooler temperature than other cultivars studied, however, when temperature increased, Monument produced longer PRL as observed at 28 °C. Such genetic variation of root growth under different temperatures is also observed in other crops. Oosterhuis (2012) reported longer taproot by 'Stoneville 4892BR' cotton at lower temperature while 'Tamcot Sphinx' produced maximum taproot at higher temperature. The differences in the root growths of different cultivars at a particular temperature is an adoptive trait, which may help the cultivar to establish quickly and start using resources earlier at that temperature compared to other cultivars.

3.3. Seed vigor index

The seed vigor index (SVI), which integrates both germination and seedling length, increased with every incremental temperature treatment of the study (Table 4). The SVI was highest at 28 °C, which was more than 54 times higher than that at 13 °C. Similar to PRL, SVI suggests that guar crop establishment improves with increasing in temperature. Increase in SVI with higher soil temperature are also reported in other crops like wheat, where improving germination temperature from 20 to 30 °C improved SVI (Buriro et al., 2011). Crops also have optimum, minimum and maximum temperatures for SVI. For example, in palmarosa optimum temperature for SVI was around 25 °C, which decreased at temperatures of 20 or 30 °C (Kumar et al. (2012). This suggests that the highest temperature of 28 °C used in our study may be still in the optimum temperature range for guar crop establishment.

Averaged over temperatures, SVI of different cultivars significantly varied. Kinman reported the highest SVI among the cultivars tested, while Matador reported the lowest (Table 4). The genetic differences for germination and total seedling length was contributing for the differences in SVI. These findings suggest that Kinman has the highest SVI for quick and uniform emergence among guar cultivars in this study.

Interaction between temperature and cultivar for SVI ($p < 0.001$) was significant. Abrupt increase in the SVI of some cultivars at different temperature ranges resulted in significant interaction between temperature and cultivar (Table 4). Kinman had higher SVI at lower temperature range (13−16 °C). Cultivar differences for SVI at a given temperature reduced with increasing temperature. Highest SVI for each cultivar was recorded either at 25 or 28 °C. Matador had the lowest SVI at temperature range of 13−22 °C, but as temperature increased further, Matador started increasing SVI more rapidly. At 28 °C, SVI was similar in Matador, Lewis, and Santa Cruz. Interestingly, Kinman had a more stable SVI than other cultivars when temperature increased from 19 to 25 °C and it was not statistically different from Judd 69 which had the numerically highest SVI at 22 and 25 °C. This suggests that Kinman will have quicker and more uniform emergence, especially in the cooler regions of the SHP. Monument responded to temperature in a unique manner; it recorded lower SVI at 13 °C, but as temperature increased to 28 °C, it recorded numerically the highest SVI compared to other

Table 6
Interaction effects of temperature and cultivar on speed of germination index of six guar cultivars grown in a dark growth chamber at temperature range of 13−28 °C. Standard error of means are shown in parentheses.

Cultivars	Speed of germination index (day^{-1})						
	Temperature						
	13 (°C)	16 (°C)	19 (°C)	22 (°C)	25 (°C)	28 (°C)	Average
Kinman	0.72 (0.04) aE	2.06 (0.11) aD	3.78 (0.18) aC	4.33 (0.12) aBC	4.88 (0.14) aB	5.92 (0.32) aA	3.33 (0.41) a
Monument	0.12 (0.01) cdF	0.59 (0.15) dE	2.36 (0.21) cD	3.90 (0.20) abC	4.96 (0.34) aB	5.92 (0.54) aA	2.40 (0.50) d
Judd 69	0.24 (0.07) bcE	1.42 (0.13) bD	3.54 (0.15) abC	4.25 (0.08) aB	4.77 (0.28) aB	5.76 (0.18) aA	2.89 (0.47) b
Matador	0.06 (0.02) dE	0.39 (0.03) dD	1.55 (0.10) dC	3.04 (0.22) cB	3.87 (0.16) cA	4.37 (0.04) bA	1.74 (0.38) e
Lewis	0.27 (0.03) bE	1.07 (0.08) cD	3.10 (0.35) bC	4.14 (0.26) aB	4.66 (0.35) abAB	4.88 (0.74) bA	2.62 (0.44) c
Santa Cruz	0.38 (0.05) bE	1.32 (0.09) bcD	2.48 (0.22) cC	3.36 (0.14) bcB	4.12 (0.18) bcA	4.30 (0.08) bA	2.39 (0.34) d
Average	0.26 (0.04) F	1.07 (0.12) E	2.75 (0.18) D	3.82 (0.12) C	4.53 (0.12) B	5.17 (0.21) A	

Values within a column followed by same lowercase letters are not significantly different at $p \leq 0.05$.
Values within a row followed by same uppercase letters are not significantly different at $p \leq 0.05$.

cultivars. Thus, it can be predicted that Monument will have the best emergence stand when temperatures are near 28 °C.

3.4. Mean germination time

Temperature not only affects germination percentage of crops, but also has significant impact on germination time. Mean germination time (MGT) decreased gradually with increasing temperature (Table 5). Pooled over cultivars, guar took more than 13 days to reach maximum germination percentage at 13 °C, but dropped to 2 days at 28 °C. The response of guar cultivars towards temperature was expected, as it is a summer annual crop that is mainly grown in subtropical region. Gresta et al. (2018) observed reduction in germination time with increase in temperature for different guar genotypes under Mediterranean conditions.Significant cultivar differences were observed for MGT when pooled over temperatures (Table 5). The highest MGT was recorded in Matador, which was followed by Monument, Lewis, Santa Cruz, Judd 69, and Kinman. The MGT for Lewis, Santa Cruz, and Judd 69 were statistically similar. This demonstrates the variation in MGT among guar cultivars and may prove to be helpful information, since a delay in germination makes seeds more susceptible to damage by predators, pathogens, etc., thus reducing the uniformity in plant stand (Queiroz et al., 2019).

At cooler temperatures (13−19 °C), MGT of all cultivars did not respond in the same way (Table 5). It was noticed that Monument had 31, 59, and 40 % higher MGT than average of four other cultivars (Kinman, Judd 69, Lewis, and Santa Cruz) at 13, 16, and 19 °C, respectively. The corresponding difference for Matador was 41, 70, and 56 % at 13, 16, and 19 °C, respectively. But as temperature increased, Monument started taking less time for MGT, and it recorded the lowest MGT at 28 °C. Although Matador had the highest MGT averaged over all the temperatures, it was the slowest to germinate in the temperature range of 13–22 °C. At lower temperature ranges from 13–22 °C, Kinman had the lowest MGT. This indicates that Kinman will take least time to germinate as compared with guar cultivars studied in this trial, when planted in the cooler temperatures in the SHP.

3.5. Speed of germination index

Temperature effect on speed of germination index (SGI) was observed in this study (Table 6). The SGI is a comprehensive measurement that combines both germination percentage and speed to magnify variations in germination among cultivars. Averaged over cultivars, SGI was less at lower temperatures and increased with increasing temperatures and the highest was recorded at 28 °C. This confirms that the number of guar seeds germinating in a day will be the most rapid when the temperature increases. Our results agree with Hu et al. (2002), who found that guar seeds will germinate the fastest at 27 °C.

Overall, SGI was the highest in Kinman across all temperatures followed by Judd 69, Lewis, Monument, Santa Cruz, and Matador (Table 6). Monument and Santa Cruz had similar SGI when averaged over all temperatures. This shows that guar cultivars do not germinate at the same rate and there are distinct differences among them. This information could prove useful to breeders improving guar germplasm.

A significant interaction for temperature × cultivar was observed for SGI ($p < 0.001$). Differences among cultivars at the same temperature were more at lower temperature ranges and these differences were reduced at higher temperatures (Table 6). Matador had the lowest numerical SGI at all the temperatures except 28 °C. Response of Kinman for SGI was promising at lower temperature range (13−22 °C) and it was significantly higher than other cultivars at 13–16 °C and 19–22 °C, respectively. This information is useful for the farmers in cooler regions of SHP, who want to plant guar with rapid establishment.

4. Conclusions

Results from this experiment indicated that currently available guar cultivars exhibited significant variations for germination and early growth under low temperature. Kinman with higher germination percent, higher seed vigor index and faster germination is suitable for lower temperature regions of the SHP, while Matador was least adaptive among all the cultivars used in this study. Identified cold-tolerant cultivar may provide number of opportunities to farmers in cooler regions. Need for growing guar in new regions of the world is predicted to increase with growing interest in fossil fuel reserve in shale formation. Guar gum is needed for fracking to efficiently extract natural gas from those reserves. Identifying genetic variation for germination and early growth under cooler conditions will stimulate guar breeding programs in multiple countries to develop locally adopted cultivars suitable for their industries. Further research should be conducted to assess genetic variation for cold tolerance among diverse germplasm from different parts of the world.

CRediT authorship contribution statement

Jagdeep Singh: Methodology, Data Collection, Original Draft and Editing. **Ivette Guzman:** Methodology, Reviewing and Editing. **Sultan Begna:** Methodology, Review and Editing. **Calvin Trostle:** Conceptualization and Reviewing. **Sangu Angadi:** Conceptualization, Funding, Methodology, Supervision, Reviewing and Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.indcrop.2020.113082.

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