Hydrothermal time model analysis of seed germination responses to osmotic stress and temperatures in *Cicer arietinum* L. varieties

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Abstract- Germination models can help predict seed germination in response to different abiotic stress factors. We used the hydrothermal time model (HTT) to study seed germination in two chickpea verities (Parbat and Bittle-98) under different water potentials (Ψ) and temperatures (T). The results indicated that the significant maximum germination percentage (G%) was recorded at 24°C and -0.3MPa, while the lowest was recorded at 6°C and -0.2 MPa. Moreover, both verities exhibited a linear increase in germination rate at different temperatures. For both varieties, the average cardinal temperatures (Ts) were 6°Cfor the base T (T_b), 18°Cfor the optimal T (T_o), and 36ºCfortheceiling T (T_c) over the confidence intervals of HTT coefficients and maximum R^2: 0.972. In addition, the highest θT1 for Parbat was recorded at 24°C and -0.3MPa ψ which decreased with decreasing ψ (-1.2MPa). The maximum θT2 value for Bittel-98 was observed at -0.3 MPa) and 24°C in comparison with the control. The highest $\psi_{b(50)}$ (base water potential at 50) for Parbat was monitored at -0.31MPa and T_c 36°C. In contrast, for Bittle-98, the highest $\psi_{b(50)}$ value was observed at the middle temperature with an irregular fluctuation pattern. The value of θH (hydro time constant) surged with the rise in T to $T_{o,}$and the continuous decline was recorded when $T>T_o$. By analyzing the seed germination data, the hydrothermal time model (HTT) can provide insight into the synergistic impacts of water deficit and altered temperature on germination of seeds in the face of future climatic changes.

Index Terms- Germination, Osmotic stress, Cardinal temperatures, Hydrothermal time constant, Water potential

I. Introduction

Chickpea (*Cicer arietinum* L. Fabaceae) is a vital pulse crop grown on both dry and irrigated soil in tropical and subtropical climate zones(Showler *et al.*, 2022). Most commonly, it is cultivated in rotation with cereal crops on well-drained black soil as the third most crucial economic pulse crop, contributing almost 20% of the world's total pulse production(Shah *et al.*, 2020). Chickpea was first introduced in the Middle East some 7 000 years ago. Currently, it is cultivated in 50 different countries over an area of 10.7 million hectares (M *ha*) with an average yield of 8.2 million tons (Khan et al., 2021). As a result of continuous climate change, the frequency and intensity of environmental stress factors have increased, adversely affecting plant metabolic processes, development, growth, and productivity (Vaughan *et al*., 2018; Li *et al*., 2019b, 2019a; Ullah *et al*., 2019; Zhang *et al*., 2021). In the development of plants, germination is a complex physiological phenomenon dependent on abiotic factors such as variations in light and temperature, water resources, soil salinity, as well as specific compounds(Bakhshandeh and Gholamhossieni, 2018; Luo*et al.*, 2021; Ullah *et al.*, 2022; Khan *et al.*, 2022).

In nature, dormancy controls germination following seasonal cycles to enhance the chances of seedling survival and growth. The establishment of a stand is crucial in determining plant density, uniformity, and management options for crops. Expensive hybrid vegetable and flower seeds must germinate quickly and uniformly to survive harsh germination conditions and produce normal seedlings (Cheng and Bradford, 1999). Water deficit and temperature are two influential abiotic limiting features that influence seed germination (SG)as well as its attributes. Germination may be reduced or terminated if the $\Psi$of the medium for germination is diminished. The range of variation between the ambient $\Psi$and the physiological threshold for seed radicle emergence is connected with the germination rate (GR). When water availability is abundant, the variation in soil temperature is a key stress factor influencing seed germination and, hence, plant establishment and survival. There are three cardinal temperatures (Ts) of SG that need to be understood when determining the optimal planting time for each crop. These are T_b (Low T, at which SG is zero), To (optimumalT; SG is maximum at this temperature), and Tc (maximum T; SG is zero at this temperature).

Despite reports of varying cardinal temperatures in some species, these parameters are usually invariant during the crop cycle (Torabi *et al.*, 2013). As a consequence of the relationship between temperature, dormancy, and germination, temperature changes may negatively affect crop establishment and emergence. Therefore, it is imperative to clarify our perception regarding the impact of several key aspects, including the species' environmental allocation patterns, seed germination conduct, and seedling metabolic processes, growth, and establishment, to optimally supervise crop plants in the continuously changing climate scenarios (Shah *et al.*, 2021).

The Chickpea (*Cicer arietinum* L.) varieties are divided into two main categories of "Desi" and "Kabuli" (Soomro *et al.*, 2021). *Cicer arietinum* L. var. Bittle-98 and *Cicer arietinum* L. var. Parbat both are "Desi" varieties sown in Pakistan under arid and irrigated areas (Shad *et al.*, 2009). Being a nutritive crop, Chickpea not only is a sufficient source of food and human health but also improves soil health. Both varieties of Chickpea can establish residual soil moisture; therefore, it offers the farmers an opportunity to cultivate twice in the growing season on the same piece of land and have the potential to fill the gap between production and consumption in developing countries (Chavan *et al.*, 1987).

Various models can be helpful in predicting seed germination in response to different abiotic stress factors. For example, the hydro-time and hydrothermal-time models (HT and HTT, respectively) can be utilized to analyze the response of seed germination to fluctuations in T and ψ individually or collaboratively (ψ × T) (Gummerson, 1986). SG in the thermal time (TT) model illustrates the germination process of seeds from three basic temperatures [(ceiling temperature (T_c), basal temperature (T_b), and optimal (T_o)Likewise, the hydro-time (HT) model has three dimensions such as Ψb (base water potential),θH (hydro time constant), and(Farahinia*et al.*, 2017)σΨb (standard deviation of Ψb) (Farahinia*et al.*, 2017). Ψb is indicative of the theoretical limit preventing seed germination (Saberali *et al.*, 2020, (Bakhshandeh *et al.*, 2019).

Using the HTT model, one can describe the concept of germination time in terms of alterations in T and Ψ in the supra-optimal (between Tb and Tc) and sub-optimal (between Tband To)temperature ranges(Bakhshandeh*et al.*, 2015). Previously, the HTT (hydrothermal time) model has been broadly used in predicting the seed germination to fluctuating T and *Ψ* in different plants species including *Daucus carota* (Atashi*et al.*, 2015), *Citrullus vulgaris* (Bakhshandeh *et al.*, 2015), *Carthamu stinctorius* (Bidgoly *et al.*, 2018), *Hordeumvulgare* (Ullah *et al.*, 2022) and *Eruca sativa* (Khan *et al.*, 2022). Given the available literature, no such and specific studies on seed germination behavior have been checked for *Cicer arietinum* L. following the HTT model.

We aimed to investigate the response of *Cicer arietinum* varieties (i.e., Bittle -98 and Parbat) seed germination behavior to alterations in T and ψ using TT, HT, and HTT model concepts; (b) to probe the expected effects on percent germination and related characteristics of both verities of Chickpea and (c) to determine seed germination cardinal temperatures. Changing climatic conditions may negatively impact the germination, seedling, and as well as productivity of economic species. Therefore, the evaluation of seed germination and related characteristics could provide valuable insight into the contribution of increasing chickpea productivity in the face of future climate changes.

II. Materials and Methods

Experimental design

Cicer arietinum L. (Bittle-98 and Parbat)) seeds with a 95% viability rate were obtained from the National Agricultural Research Centre (NARC), Pakistan. Followed by surface sterilization with 95 percent ethanol for three minutes; the seeds were gently cleaned with distilled water. Following this, the seeds were kept in a shaded area for drying at about 20°C. The experiment was performed in Petri plates following a complete block design (CBD) at different water potentials (-0.3, -0.6 -0.9, and -1.2MPa) and temperatures (6, 12, 18, 24, 30, and 36°C) in an incubator at the Department of Botany, University of Peshawar. The PEG (polyethylene glycol) was used to prepare different Ψ_s solutions (Michel and Kaufmann, 1973). Moreover, we used four accelerated aging periods (APP)(i.e.,24-hrs, 48-hrs, 72-hrs, 96-hrs, and 120-hrs).In the germination attributes assessments, 35 seeds were hydrated with 5ml water (control) and PEG6000 (solutions) on Whatman filter paper No.1. Except for reading times, an incubator placed the Petri plates randomly in darkness. There are three replications of each treatment. We examined the radicle every day and determined that it germinated when it was 2 mm long.

Analysis of data

The germination data was evaluated using a method known as repeated probit regression analysis (Onofri*et al.*, 2018; Moltchanova*et al.*, 2020). For each % at each T period, the germination rate (GR) was computed.

Thermal time (TT)

The thermal time (TT) concept was used to quantify *T*s (germination time course data of constant).
The model was as follows at sub-optimal Ts:

$$\theta T1 = TTsub = (T - Tb)t \qquad \text{Equation (1)}$$

At *Ts*, the model can be modified as follows:

$$\theta T2 = TTsupra = (Tc(g) - T)tg \qquad \text{Equation (2)}$$

As a result, the seed emergence time is inversed by the germination rate, and equations (1) and (2) can be written as (1) and (2), respectively (3):

$$GR = 1/tg = (T - Tb\,(g))/\,\theta T \qquad \text{Equation (3)}$$

T is the real T for SG, Tb(g) is the germination fraction base temperature, g is the actual time to germination fraction g, and GR(g) is seed population Grand T1 and T2.

Hydro time (HT)

(Gummerson, 1986) proposed the hydro time model, which was used to model SG in response to ψs and an accelerated ageing period. H describes the connections between solute potential ψs and GR. The following model can be used to describe the mathematical written form:

$$\theta H_{(g)} = (\psi - \psi b)tg \qquad \text{Equation (4)}$$

$$GR(g) = 1/tg = \psi - \psi b)/\theta H \qquad \text{Equation (5)}$$

H tg, and GR(g) illustrate the hydro time constant, the number of germinated seeds for radicle emergence, and the GR, respectively.

Hydrothermal time model (HTT)

HTT is the combination ofTT and HT, used to analyze SG patterns against changing T and ψ. The HTT (model) can also be used to illustrate the time for germination at all temperatures (*Ts*, *Tb*to *To*) as follows:

$$\theta HTT = (\Psi - \Psi b(g))\,(T - Tb)tg \qquad \text{Equation (6)}$$

$$\theta HTT = [\Psi - \Psi b(g) - (kT\,(T - To))]\,(T - Tb)tg$$

Equation. (7)

Where kT stands for the Boltzmann constant (the slope of Cb(g) versus T when T>To).

Germination features

We determined the cumulative germination, seed germination per day, length of plumule and radicle, and fresh and dry weight (mg) of the plumule and radicle were all used to calculate the germination indices.

Germination percentage (GP)

Germination percent is the total number of seeds per plate that germinated according to the following equation (Orchard, 1977).

$$GP = \frac{Final\ number\ of\ germinated\ seeds}{Total\ number\ of\ seeds\ sown} \times 100$$ Equation (8)

Germination energy (GE)

The GE of seeds was determined using the following formula (Maguire, 1962).

$$GE = \frac{X1}{Y1} + \left(\frac{X2 - X1}{Y2}\right) + \left(\frac{Xn - Xn - 1}{Yn}\right)$$ Equation (9)

The frequency of emerging seeds on the first, second, and subsequent days is represented by X1, X2, and Xn. Y1, Y2, and Yn are the days starting from keeping seeds on the paper of a plate up to the final day, respectively.

Mean germination time (MGT)

The MGT indicated how quickly seeds appeared in a population. A low MGT number indicates a high seed population rate and vice versa (Orchard, 1977).

$$\text{Mean Germination Time (MGT)} = \frac{\in fx}{\in f}$$ Equation (10)

The letter f denotes the number of seeds that germinated on day x.

Coefficient of the velocity of germination (CVG)

In an experiment, CVG is the speed with which seeds germinate. When all sowed seeds grow on the first day, the highest theoretical CVG value is reached(Maguire, 1962).

$$CVG = \frac{N1 + N2 + N3 \ldots Nx}{100} \times N1T1 \ldots NxTx$$ Equation (11)

Where N is the daily number of seeds germinating, and T is the time of seed keeping to seed germination**.**

Germination index (GI)

The GI was computed using the following equation(Hafez et al., 2021).

$$GI = (10 \times n1) + (9n \times n2) \ldots (1n \times 10)$$ Equation (12)

The n1, n2,...n10 denote the frequency of germinated seeds on the 1st, 2nd, and subsequent days until the final day.

Germination rate index (GRI)

The GRI indicates the percentage of seeds germinated on a respective day and time.

$$\text{Germination Rate Index (GRI)} = \frac{G1}{1} + \frac{G2}{2} + \frac{G3}{3} \ldots \frac{Gx}{x}$$

Equation (13)

Where G1 and G2 represent the percent germination on the first and second days after sowing, respectively. Gx indicates the last germination percentage on the previous day.

Seed vigor index-1 (SVI-1)

The length of three germinated seedlings from each plate was measured in centimeters and calculated using the following equation (Uddin et al., 2021).

$$\text{Seed Vigor Index (SVI-1)} = Seedlings\ length(cm) \times Seed\ Germination\ \%age$$ Equation (14)

SVI-II: (Seed vigor index-II)

That the dry weight of three seedlings from each plate was calculated and multiplied by SG percentage (Micheil *et al* ., 1973).

$$\text{SVI-II} = Seedling\ dry\ weight\ \times\ Germintion\ \%\ age$$

Equation (15)

Time to 50% germination (T50%)

T^{50}%created is determined by how long it takes for 50 percent of seeds to germinate. The following mathematical formula was followed for calculating time to 50 percent germination(Sinha *et al.*, 2018).

$$T^{50}\% = \frac{ti + (N/2 - ni)(tj - ti)}{(nj - ni)}$$ Equation (16)

Where ni N/2>Nj, N is the total number of emerged seeds, and nj and ni are the total number of seeds that emerged following consecutive counts during tj and ti.

Timson germination index (TGI)

The TGI index measures how many seeds germinate on a given day(Sinha *et al.*, 2018).

$$\text{Timson Germination Index (TGI)} = \frac{\in G}{T}$$ Equation (17)

G represents the overall germination percentage every day, and T represents the germination duration.

Data analysis

The effects of temperature and water potentials and their interactions on seed germination rate and germination parameters following models were explored using SPSS and Sigma Plot Version 11.0. The statistical calculations were performed using Excel. The values of the parameters were calculated following the concept of linear regression analysis in SPSS: ψb(50), ψb; R2, SE, Sig, F, and T-test.

III. Results

Germination responses to fluctuating temperatures (TT model)

The germination rate (GR) and germination percentage (GP)increased initially as the temperature amplitude was raised. Still, when T exceeded a specific limit, the GR and % of seeds declined. We found a significant (*P 0.05) effect of T on (1/t50) and GP of both varieties of *C. arietinum*L. The maximum GP for Parbat was observed at 24°C and the lowest at 6°C when moisture was optimum (0 MPa; control). In general, the minimum germination for both varieties was observed at 6°C and -1.2MP, whereas the maximum germination was noted at 18 to 24°C for Parbat and Bittle-98 under Ψ -0.3MPa in comparison with control. As the temperature increased to 24°C, the germination climbed from 10- to 96.3 %, then declined to 16% as the temperature increased from 24°C (T_0) to 36°C. An increase in GP was observed with accelerated aging periods and significantly (*P0.05) reduced at high T (Figure 1).

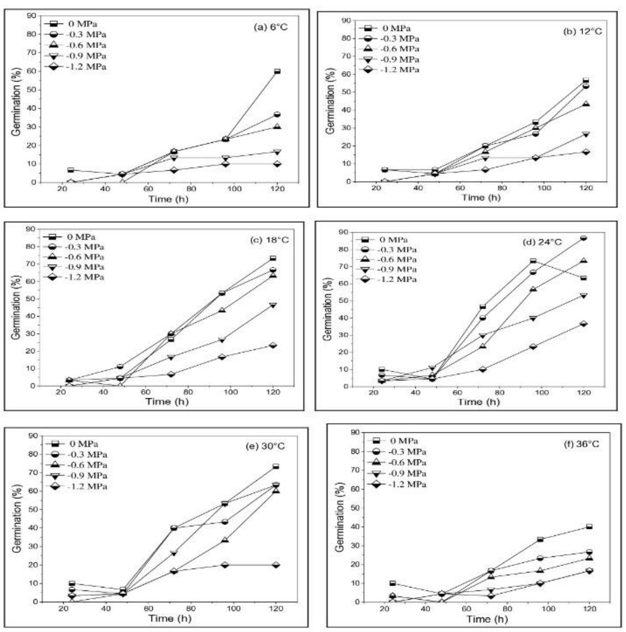

Figure 1. Cumulative germination fraction for *Cicer arietinum* var. Parbat at **(a)** 6°C, **(b)** 12°C, **(c)** 18°C, **(d)** 24°C, **(e)** 30°C and **(f)** 36°C having different water potentials (0, -0.3, -0.6, -0.9, -1.2 MPa). Symbols indicate water potential and lines indicate cumulative germination fraction predicted by hydrothermal time model.

Regardless of the variables studied, very high values for θT1 were recorded at 24°C (-0.3MPa) and declined with the dropping in Ψ (-1.2MPa) (Table 1). Comparatively to the control, the value of θT2 recorded maximum in -1.2MPa at 24°C. Based on the R2 value of 0.987, the concept of the model was well matched to germination features in controlled (distilled water).

When the data of GR was plotted with various T, a linear increase was found in the germination fraction pattern above and below the optimal temperature (*To*) (Table 1). Moreover, the significant GR(g) values (**P0.01) were raised with a reduction at all Ts. Likewise, the F and T-tests revealed a lop-sided outline having no linear trend, with the exceptionof increase in both values at 24°C and 18°C. The response of GR (g) is used to calculate the base (Tb), optimal (T_0), and ceiling temperatures (Tc).

The changes in SG time against the Ψ were investigated independently at each T using the HT. Likewise, *θH*and GR (g) data were examined using the HT concept at constant T and various Ψ. The lowest GP for Parbat wasΨ -1.2 MPa at 6°C, and the highest was Ψ -0.4 MPa at 24°C (Fig. 1). The maximum GP was found at all T in -0.2MPa and the lowest in Ψ -0.8 MPa.Moreover, the highest and lowest GP of the Bittle -98 variety was observed at 6°C and 18°C (Fig. 2). The GP was significantly lowered and delayed when the osmotic potential of the imbibition solution was decreased. This inhibitory effect was more alarming at temperatures above or below the T_0. With accelerated aging periods, both values increased by a small amount.

In response to rising temperature, both varieties' median base water potential changed irregularly, with values ranging from (Table 1). At 24°C, the base water potential's standard deviation (σΨb) at the 50 percentiles was also the lowest.

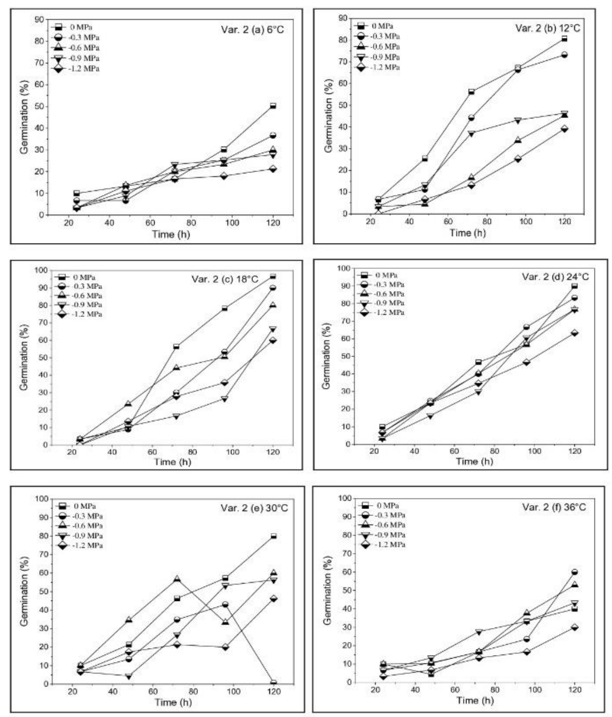

Figure 2. Cumulative germination fraction for *Cicer arietinum* var. 2 (Bittal-98) at **(a)** 6°C, **(b)** 12°C, **(c)** 18°C, **(d)** 24°C, **(e)** 30°C and **(f)** 36°C having different water potentials (0, -0.3, -0.6, -0.9, -1.2 MPa). Symbols indicate water potential and lines indicate cumulative germination fraction predicted by hydrothermal time model.

Table 1. Prediction of the hydro time model parameters for Chickpea using non-linear regression at each temperature.

Var.	Temperature	$\psi_{b(50)}$(MPa)	$\sigma\psi_b$ (MPa)	R^2	SE	F	T	Sig.
Bittle-98	6°C	-1.21	0.574	0.919	0.155	34.12	8.057	0.10
	12°C	-0.97	0.478	0.873	0.195	20.61	6.282	0.20
	18°C	-0.72	0.392	0.987	0.635	220.15	18.25	0.01
	24°C	-1.31	0.338	0.921	0.153	35.078	6.870	0.10
	30°C	-0.87	0.211	0.976	0.085	121.16	13.74	.002
	36°C	-0.880	0.113	0.247	.475	20.16	1.600	0.395
Parbat	6°C	-0.91	0.457	0.960	.109	72.00	12.65	.003^b
	12°C	-0.58	0.328	0.959	.111	69.81	12.18	.004^b
	18°C	-1.28	0.174	0.893	.179	24.92	7.07	.015^b
	24°C	-1.10	0.166	0.972	0.918	103.7	14.01	.002^b
	30°C	-1.27	0.290	0.661	0.318	5.860	3.622	.094^b
	36°C	-0.31	0.201	0.870	1.915	20.16	6.479	.021^b

Base water potential at 50 percentile ($\psi_{b(50)}$); Standard deviation in Ψ_b ($\sigma\psi_b$); Coefficient of determination (R^2); Standard error (SE); Variability between different means (F); Test (T); Level of significance (Sig).

Germination responses to T and Ψ (HTT model)

The HTT concept's predictability peaked at 18°C (R2= 0.987). PG and GR were significantly (*P0.05) affected by the interaction between T and Ψ. Based n the comparison results of the HTT model, Ψ has a somewhat higher effect on SG than T. We detected a linear trend of increasing HTT as T rose to ideal and then fell as Tc approached. Across various Ψ, the HTT values decreased as the osmotic potential decreased. The estimated cardinal temperatures of the HTT concept for Tb, To, and Tc in control were 6°C for Tb, 24°C for To, and 36°C for Tc (Table 2). Moreover, the results revealed a significant change in PG, GI, GRI, TGI, T50, GE, CVG, MGT, plumule and radicle length, SVI-I, and SV-II, compared with the control (Figs 3-8). These metrics have been negatively affected by rising Ψ (more negative) and increasing temperature. These values peaked at -0.2 MPa at 28°C. MGT and T50%, on the other hand, were found to be at their maximum values at -1.2MPa and 36°C.

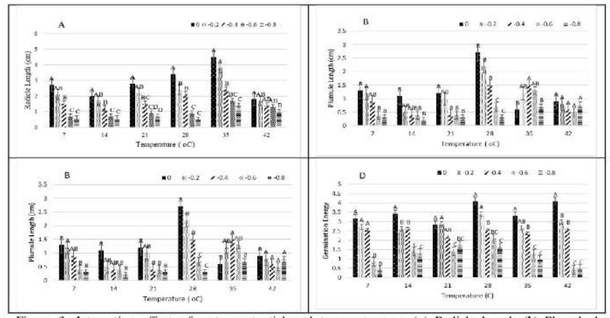

Figure 3. Interactive effect of water potential and temperature on **(a)** Radicle length **(b)** Plumule length **(c)** Germination percentage **(d)** Germination energy of chickpea var. Parbat.

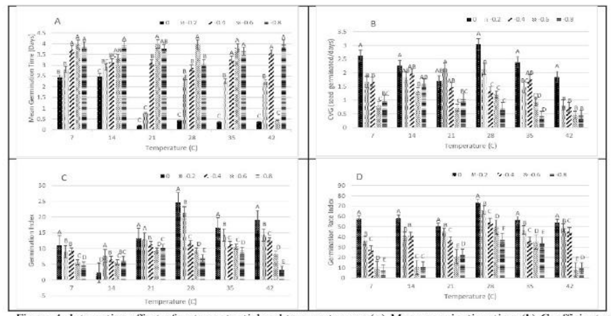

Figure 4. Interactive effect of water potential and temperature on **(a)** Mean germination time **(b)** Coefficient of velocity of germination **(c)** Germination index **(d)** Germination rate index of chickpea var. Parbat.

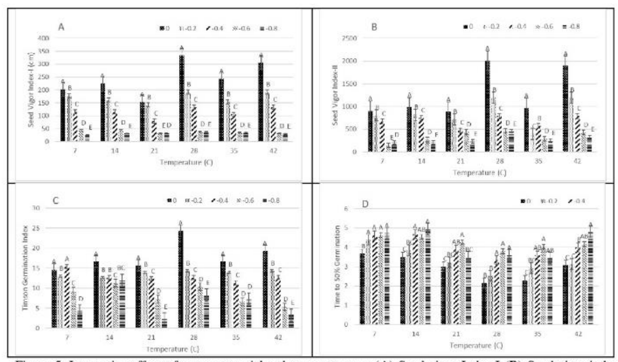

Figure 5. Interactive effect of water potential and temperature on **(A)** Seed vigor Index-I **(B)** Seed vigor index-II **(C)** Timson germination index **(D)** Time to 50% germination of chickpea var. Parbat.

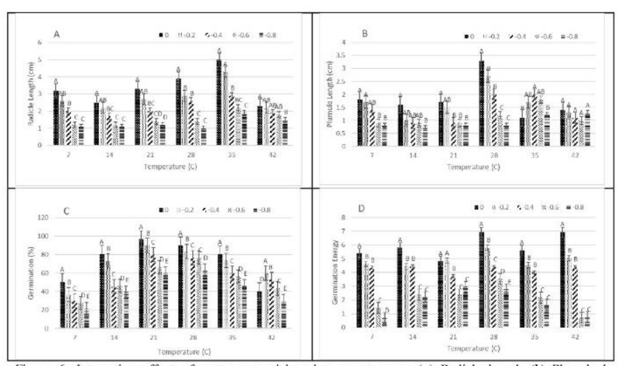

Figure 6. Interactive effect of water potential and temperature on **(a)** Radicle length **(b)** Plumule length **(c)** Germination percentage **(d)** Germination energy of chickpea var. Bittal-98.

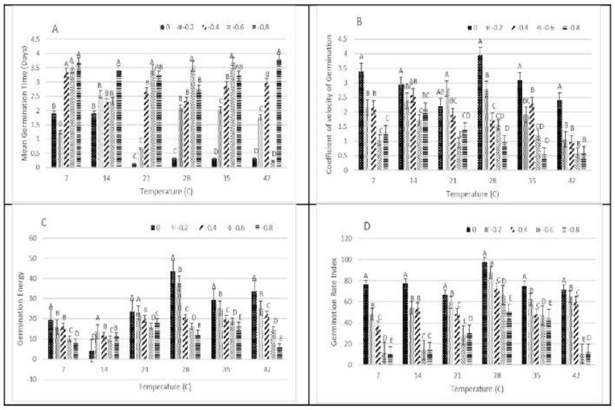

Figure 7. Interactive effect of water potential and temperature on (**A**) Mean germination time (**B**) Coefficient of velocity of germination (**C**) Germination index (**d**) Germination rate index of chickpea var. Bittal-98.

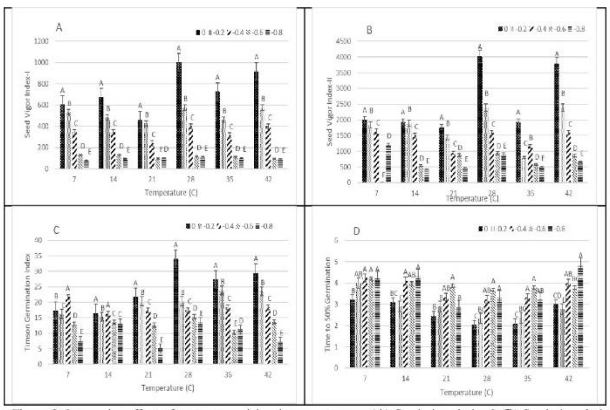

Figure 8. Interactive effect of water potential and temperature on (**A**) Seed vigor index-I (**B**) Seed vigor index-II (**C**) Timson germination index (**D**) Time to 50% germination of chickpea var. Bittal-98.

Table 2. Estimated variable values using the hydrothermal time model for describing seed germination and cardinal temperatures of *Cicerarietinum* L. at six constant *T*s at each of the following four ψs.

	Variables	*Cicer arietinum* var. Bittle-98
		Hydrothermal time model parameters
Var. Bittle-98	Ψb (50) (MPa)	-1.78
	σψb (MPa)	0.34
	θHTT (MPa °Ch^{-1})	30.14
	kT (MPa °Ch^{-1})	0.104
		***Cicer arietinum* var. Parbat**
Var. Parbat	Ψb (50) (MPa)	-1.34
	σψb (MPa)	2.65
	θHTT (MPa °Ch^{-1})	29.45
	kT (MPa °Ch^{-1})	0.104
Cardinal temperatures		
Var.Bittle-98	T_b (°C)	6
	T_o (°C)	18
	T_c (°C)	36
Var. Parbat	T_b (°C)	6
	T_o (°C)	18
	T_c (°C)	36
	R^2	0.96

Boltzmann *constant (*kT); Coefficient of determination (R^2)

IV. Discussion

The abiotic stress factors significantly impact seed germination as well as seedling's development, metabolism and growth of various crop plants (Bakhshandeh and Gholamhossieni, 2018; Bakhshandeh*et al.*, 2020b; Noor *et al.*, 2022; Ullah*et al.*, 2022). Therefore, to determine the optimal geographical location in which a species will germinate and thrive, it is necessary to thoroughly check the germination patterns and the growth of the seedlings in changing climates. In this regard, mathematical models such as TT, HT, and HTT are appropriate for determining the negative impact of these stress factors on seed germination (Bradford, 2002). Temperature (T) is one of the most destructive abiotic factors affecting seed germination in many plants (Bakhshandeh*et al.*, 2020b; Wang *et al.*, 2020).

Variation in water potential (*ψ*) is another crucial aspect limiting early seedling and seed germination(Seepaul*et al.*, 2019). Our findings also showed that both T and *ψ*had a significant impact on seed germination. Germination percentage (GP in *C. arietinum* L. decreased significantly at temperatures above and below optimal T (To) (18°C and 24°C, respectively) (Figs 3 and 5). It could be attributed to the fact that increasing temperature causes denaturation of the critical amino acids needed for seed germination and hence reduces the GP (Mollaee *et al.*, 2020). Moreover, the SG decreased with a reduction in*ψ*. Based on all six constant temperatures, the highest germination percentage was observed at -0.3MPa, and the lowest was found at -1.2MPa (Figs 1 and 2). As a consequence of the *ψ* decrease, water potential energy has been consumed and the source of water is restricted to the seed (Bradford, 2017). Previous studies validate our germination findings against *ψ(*Atashi *et al.*, 2015*;* Bakhshandeh *et al.*, 2015).

Moreover, at constant *ψ*, the values of GR(g) displayed a linear decline in correlation with temperature up to Ts and To, which corroborates previous findings on *spontaneous*(Mesgaran*et al.*, 2017). T and Tb represent the critical cardinal temperatures to construct a crop simulation model and determine the optimal planting time(Luo *et al.*, 2018). Our investigation determined the To and TC be 24°C and 36°C, respectively, in agreement with previous findings (Bakhshandeh*et al.*, 2017, 2015). In addition, we found that the values of the cardinal temperatures remained unaffected, which is in contrast with previous findings (Bakhshandeh *et al.*, 2020b, 2020a; Khan *et al.*, 2022; Ullah *et al.*, 2022). At constant *ψ*, the GR(g) values plotted against T revealed a modest decrease with an increase in T. Moreover, the θH and GR(g) results contradict the previous finding reported for *Sesamum indicum* (Bakhshandeh *et al.*, 2017)and potato(Alvarado and Bradford, 2002). However, the decrease *ψ*caused an increase in the GR(g) values. Similar findings were reported previously for lemon (Atashi *et al.*, 2014) and *Citrullus* species (Bakhshandeh *et al.*, 2015).

Moreover, the θH values were used to assess the sensitivity of varieties to research experiments and breeding practices. This study indicated that values of σΨbexhibited a linear probit trend that decreased with rising T until T_0 but then exhibited an irregular pattern at supra optimal T.Thispattern is probably due to a sudden drop in enzymatic activities and oxygen consumption during SG. So, σΨb is used as a seed lot quality indicator showing uniform SG variation(Bradford, 2017). However, utilizing approximated HT parameters (H, Ψb(50), and Ψb), portray a germination time at any T and Ψ. It is evident that the TT and HT concepts can only explain SG behaviors at supra-optimal T but cannot explain the reduction in germination when Ts>To (Bradford, 2002). Therefore, the HTT concept explains the SG at T's>To. Based on our study, the HTT value for the Parbat variety was calculated to be 29.45 MPa oCh-1, while that for Bittle-98 was 30.14 MPa oCh-1 (Table 2).

In comparison with high T and low, Bittle-98 properties are more melancholy. Comparing high and low T, SG properties are lowered than Bittle. The reductions may be attributed to the thermal decline of metabolic processes in the seed(Ekinci*et al.*, 2017; Nemeskéri and Helyes, 2019). By evaluating statistical data, cardinal temperatures, HTTs, and germination data, the HTT provides insights into the interaction between T and water availability in seed germination populations.

V. CONCLUSION

Our data revealed that T and *Ψ*, as well as their interactions with accelerated aging periods, had a significant impact on germination percentage and germination rate. The developed HTT model explains the SG behavior of *C. arietinum* at all temperatures. Both temperature extremes (6°C and 36°C) resulted in significantly decreased SG and germination properties (-1.2MPa). Moreover, according to TT, HT, and HTT models, the maximum SG was observed at 24°C and 18°C (Ψ-0.3 MPa), respectively. In contrast, the lowest and highest H values were recorded at -1.2MPa at 6°C and -0.3MPa at 24°C, respectively, at kT 0.104 MPa oCh-1 and cardinal Ts (Tb= 6ºC, To= 24 oC, and Tc=36oC). Germination is the reflection of all physiological responses of seeds. Even though actual conditions may differ from those predicted in a model, the execution may not precisely match the controlled expected model. However, a current study followed the HTT model (Liu *et al.*, 2019) and suggested that seed germination sensitivities to fluctuating T and ψ of the 13 annual xerophytes were distinctly correlated with seedling emergence in the desert ecosystem of Arizona. Based on our findings, we believe that our study may be able to calibrate and forseethe germination characteristics anticipated in the field environment.

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