RESEARCH ARTICLE

Modeling the upshots of induced temperature and water stress on germination and seedlings length of radish (*Raphanus sativus* L.) via hydrothermal time model

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Abstract

Radish (*Raphanus sativus* L.), a representative of the Brassicaceae family, is an extensively cultivated root vegetable across the world. Thermal time (TT), hydro time (HT), and hydrothermal time (HTT) models can be used to characterize the response of seed germination rate to temperature (T) and water potential (ψ). The germination behavior of radish was investigated throughout a range of constant temperatures and water potentials to evaluate the effectiveness of hydro-thermal time model and offer a data set of germination thresholds and parameters. The study was intended to simultaneously inspect the radish seed germination (SG) pattern, base water potentials ($\psi_{b(50)}$) and cardinal temperatures across varying temperatures (T_s) and PEG-6000 water potentials (Ψ_s) via the hydrothermal time (HTT) model. In a laboratory experiment *Raphanus sativus* L. seeds were germinated at four constant T_s of 15, 20, 30 and 40 °C under four different water potentials (*ψs*) of 0, − 0.2, − 0.4 and − 0.6 MPa. Germination decreased significantly at ($p \leq 0.01$) from 40% at 15 °C in − 0.2 MPa to 13% in − 0.8 MPa at 40 °C. The results also revealed that radish was more sensitive to ψ than T (p ≤ 0.01). As per the significance level of the model attributes (R^2: 0.527), the average cardinal temperatures were 15, 20 and 40 °C for the base (T_b), optimal (T_o) and ceiling (T_c) temperatures respectively. Germination energy (GE), germination rate index (GRI), germination percentage (G%), germination index (GI), mean moisture content (MMC), seed vigor index 1 and 2 (SVI-1 and SVI-2), were recorded maximum in control condition at 15 and 20 °C and minimum at − 0.8 MPa at 40 °C. The model applied here, and its attributes, may be used as a prediction tool in different SG simulation studies, each with its own set of strengths and drawbacks. The hydrothermal constant investigates the interaction influence of T and ψ on germination under diverse ecological settings using germination data, cardinal temperatures, and statistical analysis.

Keywords Germination modeling · Germination attributes · Hydro time · Thermal time · Drought stress · Radish

Abbreviations

TT	Thermal time
HT	Hydrothermal time
T_c	Ceiling temperature
T_o	Optimum temperature
TTsupra	Supra optimal temperature
$\Psi_{b(50)}$	The base Ψ of 50th percentile
T_b	Base temperature
GR	Germination rate or 1/tg
TTsub	Sub optimal temperature
T	Temperature
Ψ	Water potential
$\sigma\Psi_b$	Standard deviation of Ψ_b
Ψ_b	Base water potential
MPa	Megapascal
θH	Hydro time constant
SG	Seed germination

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Introduction

Radish (*Raphanus sativus*) is one of the important crops of the Brassicaceae family that is believed to be originated from central or western China and the Indo-Pak subcontinent.

This family contains many essential vegetables (cabbage, broccoli, cauliflower and mustard) and wildflower species (Zhang et al. 2021). Their enlarged root, hypocotyl and fresh shoots were used as a vegetable throughout the world, especially in Asian countries (Bewley et al. 2013). Radish is also cultivated for its non-saturated, non-fragrant oil extracted from mature seeds (Yara-Varón et al. 2017). It is advised for people who have jaundice, an enlarged liver, or a spleen. Because of its short growing season, it is also a popular vegetable for kitchen gardening. Its roots and leaves contain dietary fibers, sugars, essential amino acids, carbohydrates and even some unsaturated fats (oleic, erucic, palmitic and linolenic acid). It also includes minerals (calcium, potash, iron, phosphorus, manganese, magnesium and zinc) as well as water-soluble vitamins (ranging from B1 to B3, B6, B9 and C) (Banihani 2017). Radish output is projected to reach at 7 million tons per year, accounting for around 2% of all vegetable production (Shah et al. 2020a, b, c). Seed germination is highly influenced by environmental factors like light, water, temperature, and chemicals (Bakhsandeh and Gholamhossieni 2019). Among these, water potential and temperature influence the germination of non-dormant seeds (Bradford 2002). Although, it is necessary to categorize 3 cardinal temperatures of SG which is the base temperature (T_b, SG value minimum), Optimum temperature (T_o, SG value is maximum) and maximum temperature (T_c, SG value is minimum). To determine the best growing season, it is recommended to use three cardinal temperatures (T_s) for crops (Bakhshandeh et al. 2013; Parmoon et al. 2015). According to literature, based on the segmented and dent-like model, T_o maybe only point or a range of T_s which was restricted in lower T_o (T_1) and upper T (T_2) (Bakhshandeh et al. 2013). Up to now, numerous mathematical concepts have been applied to report the relationships among GR, G%, Ψ_s and T_s and their interactions ($\Psi \times T$) (Bakhshandeh et al. 2013; Atashi et al. 2014; Bewley et al. 2013). Early scholars determined individually the relationship at TTsub and TTsupra optimal T_s, by using thermal time and its derivative models. The model can be written as:

$$TTsub = (T - Tb)tg \quad \text{at sub - optimal } T \tag{1}$$

$$TTsupra = (Tc(g) - T)tg \quad \text{at supra - optimal } T \tag{2}$$

In the model, every seed percentile (t_g) is enumerated via the thermal time constant. Gummerson (1986) suggested the hydro time model (θH), which determined the rapport between GR and Ψ in the same method as the TT model:

$$\theta H(g) = (\Psi - \Psi b)tg \tag{3}$$

where θH, Ψ, $\Psi_{b(g)}$ and tg are the hydro time constant (MPa h^{-1}), in the seed growth and Ψ (MPa), the Ψ_b (MPa), characterized for a specific seed germination fraction. The HTT

model is combined from TT and θH models (Gummerson 1986). This model can evaluate t_g at all water potentials and temperatures in the sub-opt T (from T_b to T_o).

$$\theta HTT = (\Psi - \Psi b(g))(T - Tb)tg \tag{4}$$

$\sigma \Psi_b$ is the standard error of Ψ_b and $\Psi_{b(50)}$ is the base water potential of the 50th centile. The quantity of $\Psi_{b(g)}$ is different among seeds in the population, the θHTT and T_b are expected to be persistent in this concept (Gummerson 1986). Alvarado and Bradford's models, on the other hand, were unable to simulate a drop-in germination rate at T_s (2002). According to Alvarado and Bradford (2002) that there were interactions between temperature and water potential at TT supra range of temperature which was documented in watermelon (*Citrullus vulgaris* L.) (Bakhshandeh et al. 2015), *Melissa officinalis* L., potato (*Solanum tuberosum* L.) (Atashi et al. 2014), and zucchini (*Cucurbita pepo* L.) (Atashi et al. 2015). The quantity of $\Psi b(g)$ increased when the temperature increases above the optimal temperature in all of these studies (become more positive). For supra-optimal T_s, Nevertheless, Bradford (2002) modified Eq. (5)

$$\theta HTT = \left[\Psi - \Psi b(g) - (kT(T - To))\right](T - Tb)tg \tag{5}$$

Alvarado and Bradford (2002) said that the value of $\Psi_{b(50)}$ is equal to $\Psi_{b(50)}$ distribution at To and T-To is equal to To-Tb at supra optimum range of Ts, where kT is a constant the slope of the connection between $\Psi_{b(50)}$ and Ts > To. At Ts > To the models, the change in the distribution of $\Psi_{b(g)}$ with T is linear. TT sub-optimal, TT supra optimal, hydro time (HT), and hydrothermal time (HTT) models were described in general by Atashi et al. (2015) and Bewley et al. (2013).

Seed germination was predicted and defined using the HTT model for all cardinal T and ψ. As a result, the current study sought (i) to determine the factors and their interaction affecting the germination rate of radish (ii) to observe the growth phases with specified T and ψ and (iii) to derive cardinal T_s and osmotic tolerance threshold through HTT model.

Materials and methods

The seeds for this study were supplied by the National Agricultural Research Council (NARC), Islamabad, Pakistan. The seeds were sanitized for 5 min on the surface with an 85% ethanol solution, then washed with distilled water and then dried at room temperature in the shade. From July to November 2021, the experiment was carried out in the Plant Physiology Lab of the Department of Botany at the University of Peshawar, and it utilized a randomized block design (RCBD) in an incubator (Memmert

Beschickung-Loading-Model 100–800, Germany). Four water potentials of 0, − 0.2, − 0.4, and − 0.6 MPa were used in the experiment, along with a wide range of constant *Ts* of 15, 20, 30, and 40 °C. According to Michel and Radcliffe (1995), polyethylene glycol (PEG6000; Merck, Germany) was used to make solutions. A total of 40 seeds were tested for germination on Whatman No. 1 filter paper on Petri plates moistened with 15 ml distilled water and liquid PEG6000 solutions. In addition to the reading times, the Petri dishes were randomly placed in a dark incubator. For each temperature, three copies of each treatment were built. When the radicle measured 2 mm in length, seeds were considered to have germinated.

Statistical analysis

The effects of temperature changes, thermal time (TT), osmotic potentials (HT), and their interaction (HTT model) on percentage germination and germination characteristics were examined using analysis of variance (ANOVA) and IBM SPSS Statistics 26. The fundamental statistical computations were performed using Excel software. Using linear probit regression analysis in SPSS, the following parameters (R^2, Sig, T, and F values) were discovered. Graphs of seedling fraction vs. rapid aging duration were created using ORIGIN 2021 PC Corporation.

Germination parameters (GP)

The per day and cumulative germination, length, physical observation, fresh and dried weight of the seedlings were used to produce the following germination indices.

Germination percentage (G%)

Out of the total seeds put in each Petri dish, G percentage was the total number of seeds that germinated. From Orchard (1977) formula, this germination parameter was derived.

$$\text{Germination Percentage (G\%)} = \frac{Final\ number\ of\ seedling\ emerged}{Total\ number\ of\ seeds\ sown} \times 100 \quad (6)$$

Germination energy (GE)

Maguire (1962) recommended formula was used to determine seed germination energy.

$$\text{Germination Energy (GE)} = \frac{X1}{Y1} + \left(\frac{X2 - X1}{Y2}\right) + \left(\frac{Xn - Xn - 1}{Yn}\right) \quad (7)$$

The frequency of emerging seeds on the first, second, and subsequent days is represented by X1, X2, and so on. Whereas Y1, Y2, and Yn are the days from sowing to the first, second, and final day, respectively.

Germination rate index (GRI)

The GRI indicates the percentage of seeds that germinated on a certain day and time. It's calculated using Khan et al. (2019) formula.

$$\text{Germination rate index (GRI)} = \frac{G1}{1} + \frac{G2}{2} + \frac{G3}{3} \frac{Gx}{x} \quad (8)$$

G1 and G2 represent the percent germination on the first and second days after sowing, respectively, while Gx represents the ultimate germination percentage on the last day.

Germination index (GI)

The germination index provides information on germination % and speed. The GI was estimated using the formula of Orchard (1977).

$$\text{Germination index (GI)} = (10 \times n1) + (9n \times n2)...(1n \times 10) \quad (9)$$

Percent moisture content (PMC)

The percent moisture content of each seedling was calculated using the method of Maguire (1962).

$$\text{Root moisture content (RMC)} = \frac{Wet\ weight - Dry\ weight}{Wet\ weight} \quad (10)$$

Mean germination time (MGT)

The MGT index measured how quickly seeds spread over a population. A high seed population rate is indicated by a low MGT value, and vice versa. Using Khan et al. (2021) formula, this was calculated.

$$\text{Mean Germination Time (MGT)} = \frac{\in fx}{\in f} \quad (11)$$

The number of seeds that germinated on day x is denoted by the letter f.

Seed vigor index-1 (SVI-1)

Three seedlings were measured (cm) and computed from each pot using the following formula of Shah et al. (2020a).

$$\text{Seed Vigor Index (SVI} - \text{I)} = Seedlings\ length\ (cm) \times Seed\ Germination\%age \tag{12}$$

Seed vigor index-2 (SVI-2)

Dry weight was calculated for three seedlings from each pot using an electrical balance. The values were then put into an equation and multiplied by the GP, using the method of Shah et al. (2020b).

$$\text{Seed Vigor Index (SVI} - \text{2)} = Seedling\ dry\ weight\ (mg) \times Seed\ Germintion \tag{13}$$

Results

The result of the current study evaluated that T, Ψ and their interaction pointedly affected the G percentage and GR of radish, furthermore, when Ψ declined at each T the amount of GR and GP decreased.

Hydro time (HT) model

When temperature amplitude increased, the germination rate and percentage of seeds increased at first, but when T increased beyond a specific point, the GR and percentage of seeds fell. The temperature had a significant (*P 0.05) influence on germination rate (GR = 1/t50) and percentage of *Raphanus sativus* L., as shown in Table 1 Using the HT model, the variation in seed germination time courses versus water potential was examined independently at each T (R^2 ranges 0.107–0.693). This HT idea was used to assess the θH, Ψ, ψb and G% parameters for our experimental data for each constant temperature and different water potential. At 28 °C, the lowest germination percentage (13%) and highest germination percentage (40%) were measured at − 0.6 MPa and − 0.2 MPa, respectively (Fig. 1a, d). At all Ts, the maximum germination percentage was found at − 0.2 MPa and the lowest at − 0.8. (Fig. 1a–f). It was discovered that lowering the imbibition solution's osmotic potential greatly lowered and slowed germination percentage, with the inhibitory impact being more pronounced at temperatures above and below optimal T_o. With accelerated aging periods, each of these values exhibited minute increments. In contrast, to control, the maximum hydro time constant (θH) 7.20 MPa h value was calculated at − 0.2 MPa at 20 °C and the lowest 3.08 at 40 °C in − 0.6 MPa (Table 1). With the rising temperature, the median base water potential ($\psi_{b(50)}$) values

Table 1 The estimated parameters of the hydro and thermal time model to describe Raphanus sativus L. seed germination under different temperatures (Ts) and water potentials (ψs)

T	Water potential (Mpa)	TTsub	TTsupra	θH (MPa h)	θHTT (MPa h)	Hydrotime GR	Thermal time GR
15 °C	0	672.0	1680	13.4	134.4	0.015	0.01
	− 0.2	288.0	720.0	5.76	57.60	0.035	0.03
	− 0.4	288.0	720.0	5.76	57.60	0.035	0.03
	− 0.6	384.0	960.0	7.68	76.80	0.026	0.03
20 °C	0	703.6	1759	14.0	140.7	0.014	0.01
	− 0.2	351.3	878.4	7.20	70.27	0.028	0.03
	− 0.4	351.3	878.4	7.02	70.27	0.028	0.03
	− 0.6	351.3	878.4	7.02	70.27	0.028	0.03
30 °C	0	639.3	1598	12.7	127.8	0.012	0.02
	− 0.2	319.6	799.2	6.39	63.93	0.031	0.03
	− 0.4	319.6	799.2	6.39	63.93	0.031	0.03
	− 0.6	415.6	1039	8.31	83.13	0.024	0.02
40°C	0	672.0	1680	13.4	134.4	0.019	0.01
	− 0.2	319.6	799.2	6.39	63.93	0.031	0.03
	− 0.4	159.3	398.4	3.18	31.87	0.063	0.06
	− 0.6	159.3	398.4	3.08	31.87	0.064	0.06

T temperatures, *ψ* water potential, *TTsub* thermal time constant at sub-optimal temperature, *TTsupra* thermal time constant at supra-optimal temperature, *θH* hydrotime constant, *θHTT* hydrothermal time constant, *GR* germination rate
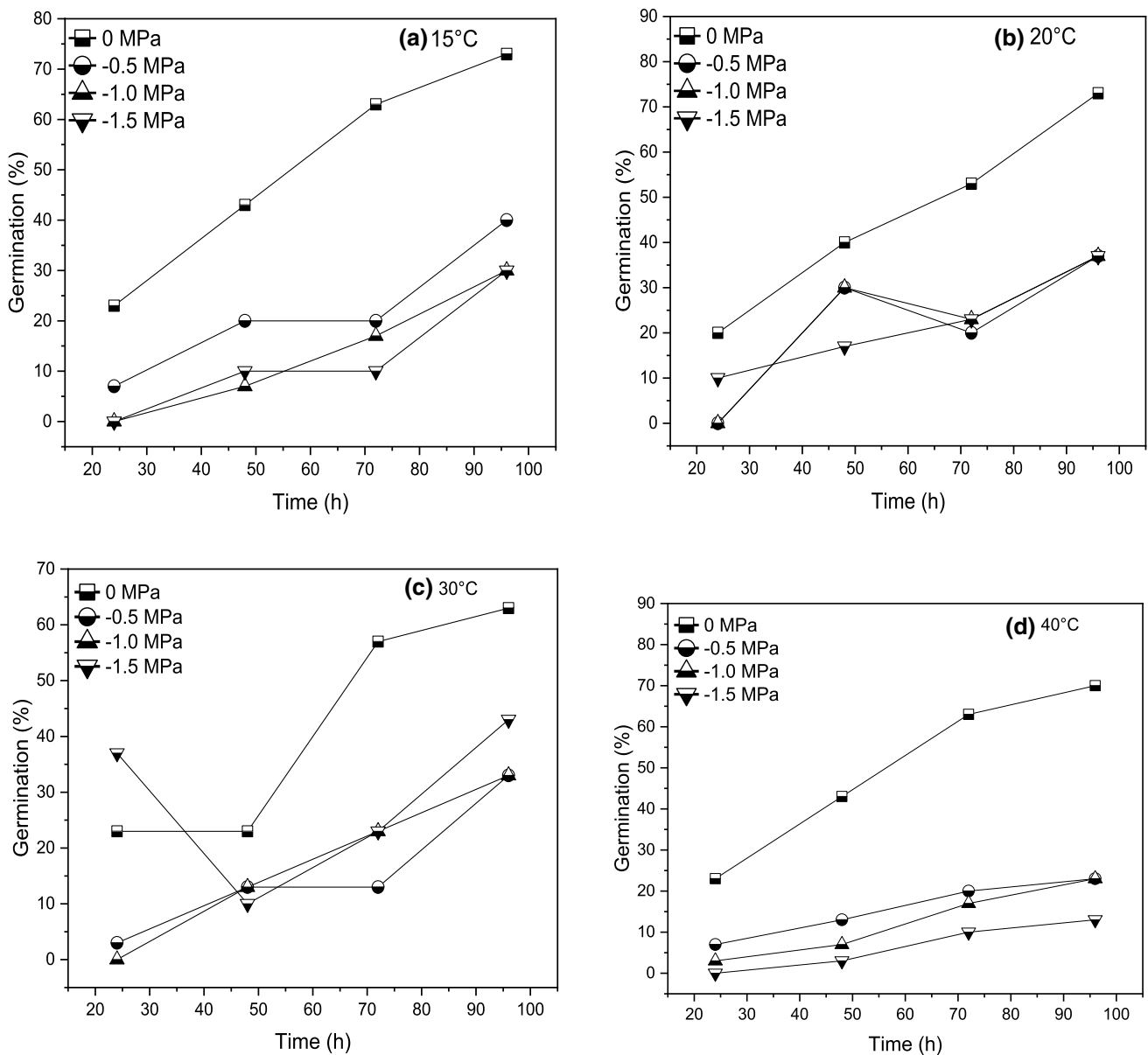
Fig. 1 Cumulative germination fraction for *Raphanus sativus* at **a** 15 °C, **b** 20 °C, **c** 30 °C, and **d** 40 °C having different water potentials (0, − 0.2, − 0.4, and − 0.6 MPa. Symbols indicate water potential and lines indicate cumulative germination fraction predicted by hydrothermal time model

fluctuated erratically, ranging from − 1.11 to − 0.23 MPa (Table 2). At 40 °C and − 0.6 MPa, the GR of the HT idea revealed a surprisingly high value (Table 2).

Thermal time model

The maximum GP was measured at 15 °C and the minimum at 30 °C at optimal moisture (0 MPa; control). In comparison to control, minimum germination of 13% was found at 30 °C under − 0.6 MPa while a maximum of 40.67% was reported at 15 °C under − 0.2 MPa. It indicates that when the water potential at each T decreases, GP decreases (Fig. 1a–d). In

the overall experiment, GP was recorded maximum after the 4th day in 0 MPa (Fig. 1a–d). In general, GP increased with the accelerated aging period (AAP) of 24, 48, 72 and 96 h and significantly ($^*P \leq 0.05$) reduced with high temperature. Furthermore, with the decrease of Ψ from 0 to -0.6 MPa, germination percentage (G%) decreased from 40 to 13% in contrast with the 0 MPa, respectively (average for all AAP levels). According to the findings, at 20 °C in − 0.6 MPa, a very high TTsub value was recorded, but no distinct pattern of growing or decreasing was seen with water potential and temperature (Table 1). The supra optimal temperature (TTsupra) value was similarly greatest in − 0.6 MPa

Table 2 Prediction of the hydrotime model parameters of *Raphanus sativus* seed germination using non-linear regression at four constant *T*s (15, 20, 30, 40 ℃) each having the following *Ψ*s (0, − 0.2, − 0.4 and − 0.6 MPa)

Temperature	θ_H (MPa h)	$\Psi_{b(50)}$ (Mpa)	$\sigma\Psi_b$ (Mpa)	R^2	SE	F	Sig
15 °C	124.8	− 0.41	0.23	0.527	49.85	24.92	0.03
20 °C	101.19	− 0.82	0.13	0.598	35.60	103.70	0.01
30 °C	124.8	− 1.11	0.57	0.107	47.13	5.860	0.02
40 °C	100.8	0.23	1.57	0.693	48.34	20.16	0.05

θH hydrotime constant, $\Psi_{b(50)}$ base water potential for 50% seed germination, $\sigma\Psi_b$ standard deviation for $\Psi_{b(g)}$, R^2 coefficient of determination, variability between different means (F), level of significance (Sig)

at 30 °C as compared to the control. With an R2 value of 0.693, the thermal time concept is well suited to germination fraction data in PEG6000 (Table 2). When the GR was plotted against different temperature percentiles, the GR pattern showed a linear rise with rising temperature and water potential (Table 1). $\psi_{b(50}$ was observed maximum at 40 °C. Similarly, the F tests indicated a lopsided pattern with no linear pattern, except a highest at 20 °C (Table 2). The basic, optimal, and ceiling temperature values are computed using these GR responses at first.

Hydrothermal time model (HTT)

The hydrothermal time model may be used to quantify SG responses to incorporate the influence of *T* and ψ over the thermal threshold (T_b) and the hydro threshold (ψ_b). At TTsupra (T > T_o), the HTT concept prediction was highest (R2 = 0.693 at 40 °C) compared to TTsub (R^2 = 0.527) (Table 2). The interaction between temperature and water potential had a significant impact on germination percentage and germination rate (*P 0.05). The HTT model's

Table 3 Estimated parameter values using the hydrothermal time model (HTT) for describing *Raphanus sativus* seed germination.

Variables	*Raphanus sativus* L.
Hydrothermal time parameters	
Ψb (50) (MPa)	− 0.41
σψb (MPa)	0.57
θHTT (MPa C h⁻¹)	1008
kT (MPa C h⁻¹)	0.104
Variables	Cardinal temperature
T_b (°C)	15
T_o (°C)	20
T_c (°C)	40
R^2	0.527

R^2 the coefficient determination, $\sigma\psi b$ standard error, Ψ_b (50) base water potential at 50 percentiles, θHTT hydrothermal time, kT Boltzmann constant

comparison results revealed that the influence of *Ψ* on SG is somewhat higher than that of *T*. In comparison to control, the maximum hydrothermal time constant (θHTT) value of 76.8 MPa h was observed at 15 °C in − 0.6 MPa. As the temperature rises, θHTT shows an uneven pattern. In the control, the predictable cardinal temperatures of the hydrothermal time model concept were 15 °C for Tb, 20 °C for To, and 40 °C for Tc (Table 3). Graphs plotting the germination characteristics versus T and water potential were used to display the data. In contrast to the control treatment, statistical analysis and graphical presentation demonstrated a significant change at (P 0.05) in germination percentage (G%), germination energy (GE), mean moisture content (MMC), mean germination time (MGT), germination index (GI), germination rate index (GRI), seed vigor index-I and II (SVI-I, and II) (Figs. 2a–d, 3a–d).

Discussion

Studying germination patterns under the impact of numerous abiotic conditions was essential to find a suitable geographic region where a species might sprout and establish itself effectively. In this regard, mathematical models (such as the TT, HT, and HTT models) assist in determining and quantifying the influence of various abiotic variables on SG time courses in seed lots (Bradford 2002; Shah et al. 2021). Temperature is one of the most damaging abiotic stressors that affect SG in a variety of plants (Wang et al. 2020; Bakhshandeh et al. 2020b). Water potential stress is another key environmental element that limits SG and early seedling development (Bradford and Still 2004). Temperature and water stress both have a substantial impact on SG, according to our findings. Our observations revealed that at *T* above and below T_o (15 °C), the G% of *Raphanus sativus* reduced dramatically (Fig. 2a). The thermal denaturation of key amino acids necessary for seed germination causes a drop in G%. (Mollaee et al. 2020). Similarly, when the water potential decreased, the decreasing pattern in germination percentage continued. At all four Ts, the maximum germination percentage was found in − 0.2 MPa and the minimum
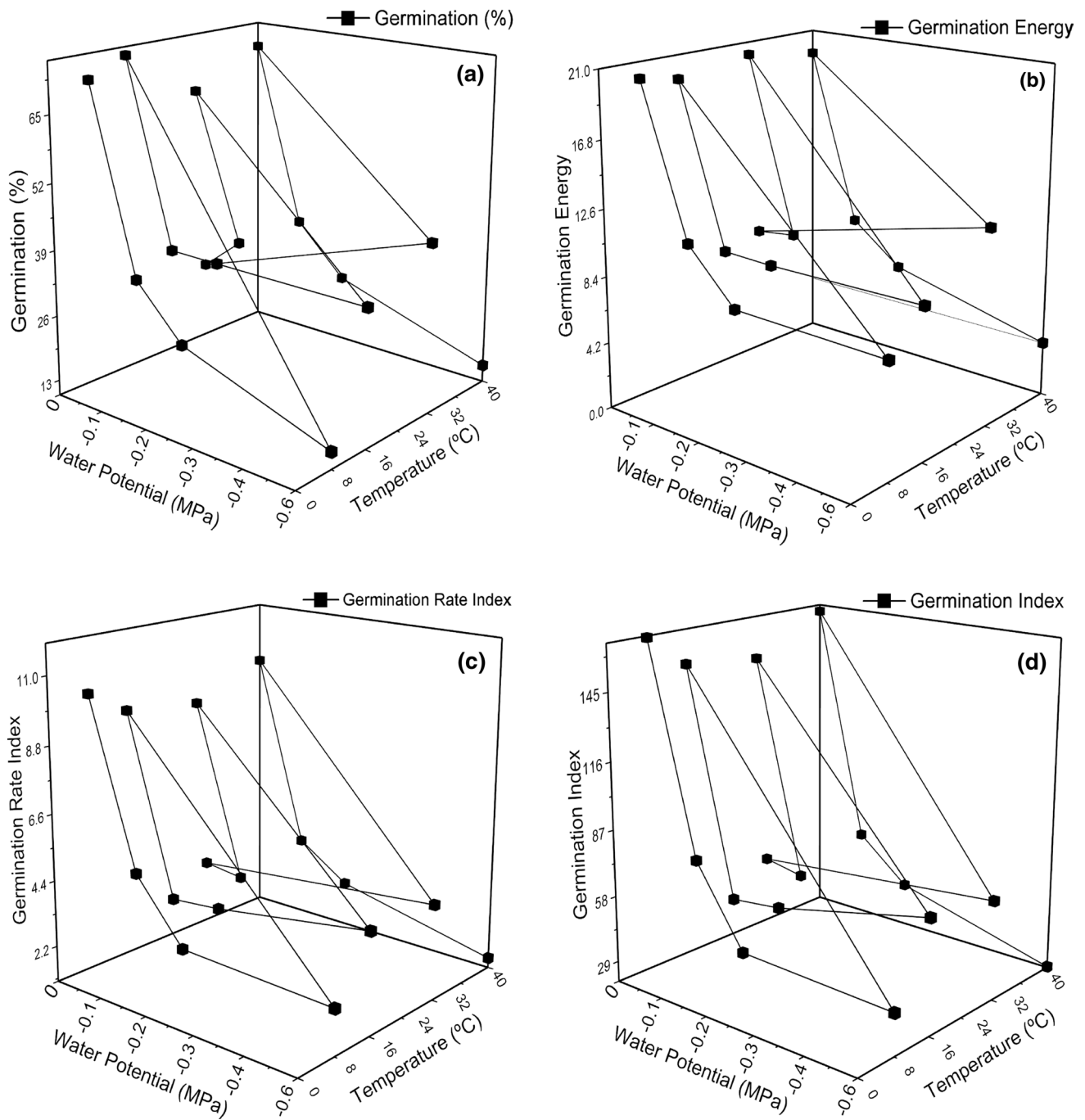
Fig. 2 Interaction effect of water potential and temperature on **a** germination percentage, **b** germination energy, **c** germination rate index and **d** germination index of *Raphanus sativus* seeds

in − 0.6 MPa when compared to control (Fig. 1a–d). The use of water potential energy as a result of decreasing ψ has restricted the availability of water to seed (Bradford 2017). For watermelon and zucchini, Bakhshandeh et al. (2015), Atashi et al. (2015) can validate our germination findings versus water potential. The GR exhibited a linear decreasing association with the temperature at constant water potential, which is similar to the TT findings on *Hordeum sponataneum* (Mesgaran et al. 2017). Several investigations used hydro time (HT), thermal time (TT), and hydrothermal time (HTT) models to analyze and anticipate seed population germination responses under various climatic conditions.
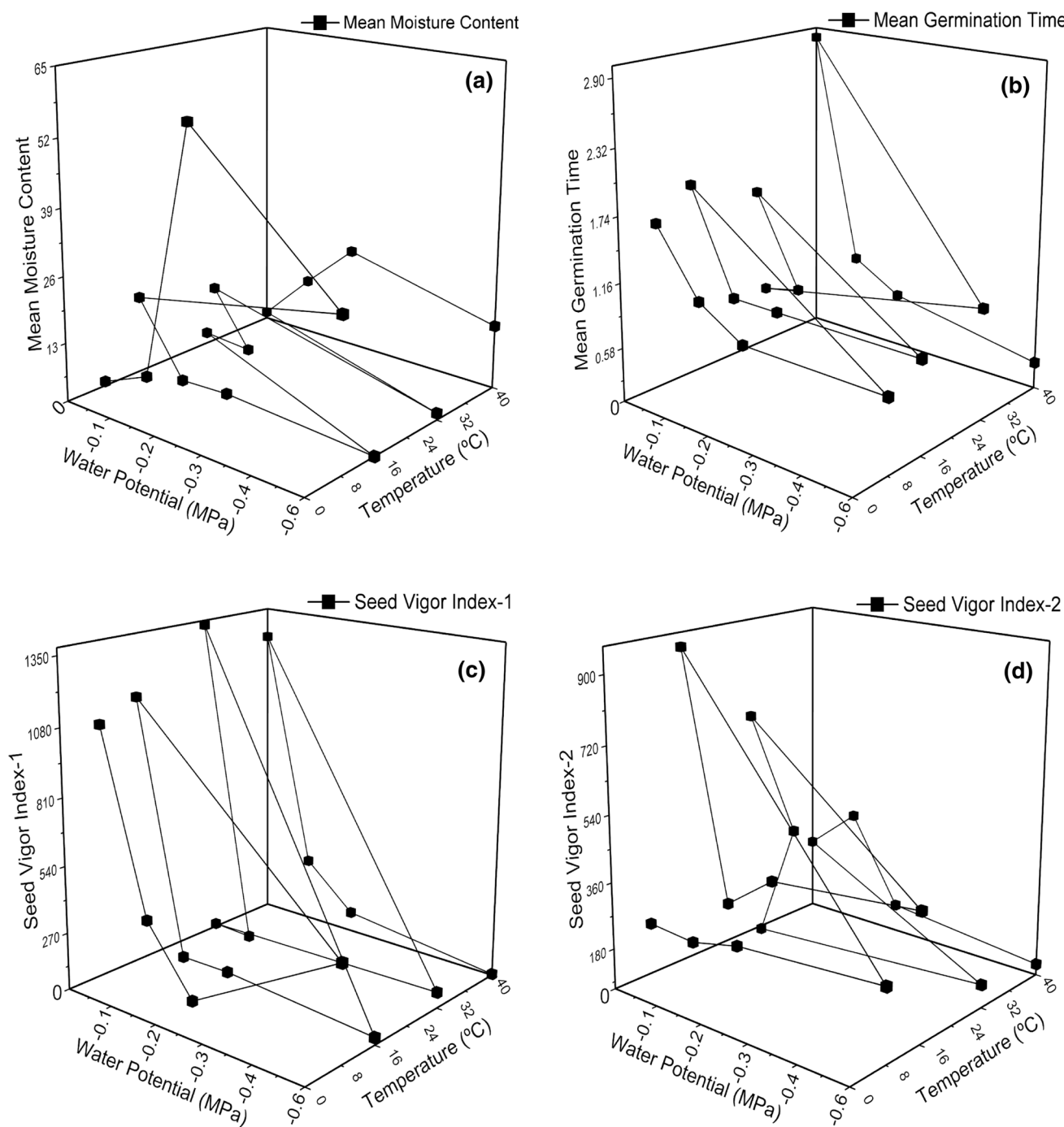
Fig. 3 Interaction effect of water potential and temperature on **a** mean moisture content, **b** mean germination time, **c** seed vigor index-1, **d** seed vigor index-2

Because they are simple and give a clear biological interpretation of the parameters, these models are popular tools for both agronomical and fundamental research (Khan et al. 2022; Ullah et al. 2022).

Table 3 shows that the minimum temperature (T_b) for radish observed in our experiment is 15 °C, below which the germination rate decreases and it will become difficult for a plant to continue its physiological processes. The Tb is a critical cardinal temperature for constructing a crop simulation model and determining the best growth time (Luo et al. 2018). The optimum temperature (T_o) at which barley germination was maximum was 20 °C. The ceiling temperature (T_c) above which plants cannot continue their physiological and biochemical activities was 40 °C. Hatfield

and Prueger (2015) found that the temperature spectrum for seed germination has three checkpoints, known as cardinal temperatures *(Ts)*, that are critical for managing the seed germination process. In the laboratory, seeds are usually kept at a constant temperature, but in the field, they experience a wide range of temperature swings. Seeds accumulated less thermal time under changing *T* circumstances than seeds accumulated under constant temperature conditions (Saberali et al. 2020). In our experiment, the cardinal temperature values were unaffected by water potential, which contradicted with (*Daucus carota)* Mesgaran et al. (2017), (*Retama raetam*) Abdellaoui et al. (2019) and corroborated Bakhshandeh et al. (2020a). The quantity of θH produced by water potential increased with rising T, and germination fractions increased up to a certain point. The θH and GR(g) results contradict Bakhshandeh et al. (2015) findings in *Sesamum indicum* and Alvarado and Bradford (2002) findings in potato.

The GR values increased when the water potential was reduced, which is consistent with the findings of Bakhshandeh et al. (2015) for watermelon and Atashi et al. (2014) for lemon balm. The θH values were used to classify cultivars and varieties according to their sensitivity to water potential in research investigations and breeding programs. The at $\psi_{b(50)}$ displayed an uneven pattern, with the lowest at 30 °C in -1.11 MPa and the highest at 40 °C in 0.23 MPa (Table 2). Bakhshandeh et al. (2015) discovered that thermoinhibition caused $\psi_b(50)$ values to be minimal at TTsub and positive (increasing) at TTsupra. The findings indicated that $\sigma\Psi_b$ values followed an irregular probit at all Ts. This has been linked to a decrease in enzyme activity and oxygen consumption during seed germination time. The $\sigma\Psi_b$ is used to show consistent fluctuations in seed germination within a seed lot (Bradford 2017). However, we may simply anticipate whole germination time courses at any temperature and water potential using estimated HT parameters $\Psi_{b(50)}$, $\sigma\Psi_b$ and θH. The TT and HT ideas have been effectively used to describe SG behaviors at various temperatures (sub and supra) and water potentials in a variety of studies. However, the TT idea failed to forecast the decline in germination rate when *Ts > To* at suboptimal *Ts* (Bradford 2002). As a result, Bradford and Still (2004) proposed the HTT model to solve the problem. The HTT idea is now a reliable tool for investigating how environmental conditions (*T* and *Ψ*) combine to impact SG in seed lots (Bradford, 2002 and Bakhshandeh et al. 2015). The θHTT for radish was calculated to be 1008 (MPa °Ch^{-1}) (Table 3).

Seedling growth metrics such as germination percentage , germination rate index, germination index, germination energy, and SVI-I and II are reduced by high temperature and low water potential. These declines are induced by high T and low *Ψ* due to thermo-inhibition of cellular activities and chemical kinetics in the seed (Ekinci et al. 2017; Nemeskéri and Helyes 2019). These stresses have the greatest impact on crop agronomy since these characteristics represent the component that farmers and consumers are most concerned about (Ekinci et al. 2017). The HTT provides a vision into the interaction influence of temperature and water potential on SG populations based on statistical analysis, cardinal temperatures, θHTT, and germination findings.

Conclusions

Our findings revealed that T, water potential, and their interactions with accelerated aging periods had a substantial impact on GR and G%. The proposed HTT model has a clear physiological meaning and defines the germination percentage behavior of *R. sativus* at all T_s and $\Psi_{s.}$ in 40 °C, the GR and germination properties were significantly lowered, and the water potential was significantly reduced (-0.6 MPa). According to the TT and HT models, the maximum TTsub and TTsupra values were observed at -0.6 MPa at 30 °C, the minimum and maximum θH values were observed at -0.6 MPa at 40 °C and at -0.6 MPa at 15 °C, and the predicted θHTT average value is 1008 MPa °Ch^{-1}, $\Psi_{b(50)}$ is -0.41 MPa and $\sigma\Psi_b$ value 0.57 MPa at k_T 0.104 MPa °Ch^{-1} and cardinal T_s ($T_b = 15$ °C, $T_o = 20$ °C and $T_c = 40$ °C. However, these parameters characterized germination niche and can be useful to predict germination capacity under different conditions of the environment. To determine the physiological condition of radish seed populations, the HTT model gives a complete quantitative description of *R. sativus* SG. Moreover, the physiological status of *R. sativus* seed populations, the hydrothermal time model ultimately offers a thorough quantitative description of *R. sativus* seed germination. The presented biological parameters can be easily used to predict germination capacity and germination time among seed populations under different environmental factors, but further study is needed to develop a halothermal time model for saline conditions. In addition, researchers should also focus on application of priming treatments for regulating the potential of germination tolerance to PEG-induced osmotic stress response to saline conditions.

Data availability All the data are available in the manuscript.

Declarations

Competing interests The authors have no conflict of interest.

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