PLANT SCIENCE TODAY
Vol 13(sp1): 1-9
https://doi.org/10.14719/pst.13099

eISSN 2348-1900

RESEARCH ARTICLE

Seed germination dynamics of *Carum carvi* L. under different temperature regimes and growth regulators

Anand Singh Bisht[1]*, Priyanka Sharma[2], Shweta B Kukreti[3], Uday Bhanu Pratap[3] & Bijendra Lal[3]

[1]Department of Basic and Social Sciences, College of Forestry, Veer Chandra Singh Garhwali Uttarakhand University of Horticulture and Forestry, Bharsar, Pauri Garhwal 246 123, Uttarakhand, India
[2]Department of Medicinal and Aromatic Plants, College of Horticulture, Veer Chandra Singh Garhwali Uttarakhand University of Horticulture and Forestry, Bharsar, Pauri Garhwal 246 123, Uttarakhand, India
[3]Department of Forest Products and Utilization, College of Forestry, Veer Chandra Singh Garhwali Uttarakhand University of Horticulture and Forestry, Bharsar, Pauri Garhwal 246 123, Uttarakhand, India

*Correspondence email - drbishtas@gmail.com

Received: 06 December 2025; Accepted: 26 February 2026; Available online: Version 1.0: 08 April 2026

Cite this article: Anand SB, Priyanka S, Shweta BK, Uday BP, Bijendra L. Seed germination dynamics of *Carum carvi* L. under different temperature regimes and growth regulators. Plant Science Today (Early Access). https://doi.org/10.14719/pst.13099

Abstract

Seed germination is a crucial stage in the crop life cycle. Laboratory experiments were carried out to assess the germination performance of *Carum carvi* L. seeds and to evaluate the effects of different temperatures and plant growth regulators on their germination behaviour. The present investigation consisted of fifteen treatment combinations, including 3 temperature levels (15, 20 and 25 °C) and 4 concentrations (25, 50, 75 and 100 ppm) of 3 chemical treatments, i.e., Gibberellic Acid (GA_3), Naphthalene Acetic Acid (NAA) and thiourea, arranged in a factorial completely randomized design (CRD). Various germination and growth parameters were recorded during the study and the results revealed that among the different treatment combinations, 20 °C combined with thiourea at 100 ppm was the most effective in enhancing all germination-related traits. The temperature of 15 °C was also found suitable, showing germination performance nearly comparable to that observed at 20 °C. Initial germination was observed after 3 days, with a mean daily germination (MDG) rate of 0.43 seeds day^{-1}, total germination of 65.33 %, germination energy (GE) of 22 %, speed of germination of 1.16 seeds day^{-1}, shoot length (SL) of 5.21 cm, root length (RL) of 3.50 cm and a correspondingly higher seedling vigour index (SVI). However, further studies are required to determine whether increasing thiourea concentration would exert a positive or negative influence on germination. Overall, the treatment combination of 20 °C × thiourea at the rate of 100 ppm was the most effective in enhancing seed germination performance of *C. carvi*.

Keywords: caraway seed; growth regulators; seed germination; temperature

Introduction

Carum carvi L. (Caraway) is one of the oldest medicinal and aromatic crops known to have a pleasant aroma and is used in the pharmaceutical, perfumery and food industries. It is commonly known as the *C. carvi* and is used for various therapeutic purposes. It is considered the most important medicinal and aromatic plant that contains volatile oils(1). The plant *C. carvi* occurs wild in India to a limited extent in the temperate regions of the western Himalayas in Kinnaur and Chamba districts of Himachal Pradesh, in the Ladakh region of Jammu and Kashmir and in the Chakrata hills and Chamoli district of Uttarakhand at 1800–2500 m above mean sea level (2). It is a biennial herbaceous plant belonging to the Apiaceae family, having 30–80 cm in height, with narrow finely grooved leafy stems, producing a deep taproot and a rosette of dark green, finely cut, feathery leaves, generally open from late April onwards and are succeeded by fruits of 3–6 mm long and light brown, ripening from early July (3).

Seeds have a pleasant aromatic odour and contain crude fibre, volatile oil, protein, resin and several trace elements. After distillation, the dried crushed seeds gave a pale yellow or light brown essential oil (4). Fruits are used as culinary spices because of their pleasant flavour (5–7). It has been used in folk medicine; recently, *C. carvi* has shown good antioxidant activity and possesses antifungal and antibacterial properties (8, 9). It also exhibits antimicrobial, anticancer, diuretic and other pharmacological activities. It improves lactation in nursing mothers and is used as a potato sprouting inhibitor (10). Given the high economic and medicinal importance of these bioactive constituents, successful cultivation largely depends on effective propagation techniques. The only feasible method for propagating *C. carvi* is through direct sowing of dried mericarps, which often results in uneven germination under field conditions (11). Achieving uniformity, rapid germination and vigorous seedling emergence in direct-seeded crops is crucial, as these factors significantly influence final yield, quality and overall profitability (12). *Carum carvi* seeds generally exhibit a germination capacity of about 60 % (13). However, the germination rate (GR) is equally important for optimising seed performance by ensuring the timely utilisation of essential resources surrounding the seeds, particularly in arid and semi-arid environments.

Temperature is an important environmental factor that influences the induction of seed dormancy during seed development and its expression during germination (14–16). Optimum seed germination and seedling emergence occur at relatively moderate temperatures (20–25 °C). An intermediate germination temperature (20 °C) allows different genotypes to express varying degrees of seed dormancy, whereas a high temperature (30 °C) allows only seeds of genotypes with very low levels or no dormancy to germinate. The ideal temperature maximises germination in the shortest time (17). In addition to temperature, the role of plant growth regulators in enhancing crop production has also been recognised (18). These play an important role, as small quantities regulate various physiological processes and balance the source and sink, thereby increasing productivity (19). The effect of foliar application of glycine and tryptophan, each applied individually at concentrations of 50, 100 and 150 ppm, on the vegetative growth, fruit yield, essential oil production and plant hormonal balance of *C. carvi*. The study reported a positive response of *C. carvi* plants to the application of both amino acids, indicating their potential to enhance growth performance, yield attributes and metabolic activity (20). Understanding hormonal responses helps in elucidating how treatments affect vegetative growth, yield and secondary metabolite production in *C. carvi*. Therefore, the present study investigated the germination behaviour of *C. carvi* collected from natural habitat in response to temperature and treated with gibberellic acid (GA_3), naphthalene acetic acid (NAA) and thiourea. Then, the physiological response to temperature in the seeds was investigated. Here, we have documented the role of the parent plant habitat in the emergence of such a response in its offspring to these treatments. Such knowledge can be useful for selecting, domesticating and cultivating the appropriate ecotypes of *C. carvi*.

Materials and Methods

Seeds of Carum *carvi* L. were collected from the Chamoli district of Uttarakhand and carefully sorted to obtain uniformly sized, fully mature, healthy and disease-free seeds. Different concentrations of GA_3, NAA and thiourea (25, 50, 75 and 100 ppm) were prepared and seeds were soaked in the solution for 24 hr followed by washing thoroughly. The seeds were then transferred to Petri dishes (25 seeds per Petri plate) with 3 replicates and were kept carefully in an incubator for 30 days, maintained at temperatures of 15 °C (T_1), 20 °C (T_2) and 25 °C (T_3) separately.

The mean daily germination (MDG) was calculated as the cumulative percentage of full seed germination at the end of the test divided by the number of days from sowing to the end of the test (21). Germination energy (GE) was calculated as the percentage of the total number of seeds that germinated at the peak, generally defined as the highest number of germinations within a 24 hr period and expressed as a percentage (22). The seedling vigour index (SVI) was derived from standard germination and seedling growth parameters (23). It is expressed as a total number and is calculated as follows:

Seedling vigour index (SVI)-I

= Germination (%) × Average seedling length (cm) (Eqn. 1)

The statistical analysis was carried out for each observed character under the study using OPSTAT. The data were analysed by using standard statistical procedures in the factorial completely randomized design (CRD) (24). The temperature regimes and the concentrations of growth regulators used in the study is illustrated in Table 1, 2 respectively.

Table 1. Temperature regime treatments used in the experiment

Treatment Code	Temperature
T_1	15 °C
T_2	20 °C
T_3	25 °C

Table 2. Concentration levels of gibberellic acid, naphthalene acetic acid and thiourea used as experimental treatments

Concentration of GA_3	Concentration of NAA	Concentration of thiourea
G1: Control	N1: Control	U1: Control
G2: 25 ppm	N2: 25 ppm	U2: 25 ppm
G3: 50 ppm	N3: 50 ppm	U3: 50 ppm
G4: 75 ppm	N4: 75 ppm	U4: 75 ppm
G5: 100 ppm	N5: 100 ppm	U5: 100 ppm

Results and Discussion

Period required to initiate germination

The initiation of germination was significantly affected by temperature, growth regulators and their interactions (Table 3). Across all the treatments, the minimum number of days taken to initiate germination was recorded at 15 °C (T_1), followed by T_2, while the delayed germination was observed at T_3. Among different concentrations of growth regulators, GA_3 at 50 ppm showed the earliest germination (3.67), while the control took 8.22 days to initiate germination. Naphthalene acetic acid showed a minimum (4.22 days) germination time at 50 ppm and thiourea was most effective at 100 ppm (3.44 days). The interactive effects were also significant. T_2 with GA_3 at 50 ppm took the minimum time (3 days) to initiate germination, while at 25 °C with thiourea 100 ppm, germination was delayed up to 6.07 days. Table 3 showed significant effects of temperature, GA_3 concentration and their interaction (T × G) at 5 % level of significance, indicating differential hormonal response under varying thermal conditions.

Mean daily germination

Mean daily germination (MDG) varied significantly with temperature and treatments. The maximum (0.28) MDG was recorded at 20 °C followed by 15 °C (0.22) while the minimum (0.16) daily GR was recorded at 25 °C. Among the plant growth regulators, thiourea at 100 ppm showed the highest (0.34) MDG, followed by NAA at 50 ppm (0.31). However, the control treatment showed consistently poor GR (0.07). Interactive effects revealed that 20 °C with thiourea at 50 ppm promoted the maximum (0.43) MDG, whereas it was lowest (0.07) in 25 °C with NAA at 100 ppm (Table 4). Similar results were reported: soaking *Berberis jaeschkeana* seeds in 20 µM thiourea for 72 hr substantially improved germination characteristics, including rate, final percentage and mean germination time (25).

Table 3. Effect of different temperatures and treatments on days taken for initial germination (days)

Temperature (T)	Gibberellic acid concentration (G)						Naphthalene acetic acid (N)					Thiourea concentration (U)				
	Control	25 ppm	50 ppm	75 ppm	100 ppm	Mean	25 ppm	50 ppm	75 ppm	100 ppm	Mean	25ppm	50 ppm	75 ppm	100 ppm	Mean
T_1 (15 °C)	8.67	4.00	3.67	4.67	5.00	**5.20**	6.33	5.00	4.33	5.00	**5.87**	4.33	5.67	4.33	3.67	**5.33**
T_2 (20 °C)	5.67	5.33	3.00	4.33	3.67	**4.40**	4.00	3.67	5.33	4.00	**4.53**	3.33	3.67	4.33	3.00	**4.00**
T_3 (25 °C)	10.33	4.33	4.33	5.33	6.00	**6.07**	7.00	4.00	5.00	4.00	**6.07**	5.00	5.67	5.67	3.67	**6.07**
Mean	**8.22**	**4.56**	**3.67**	**4.78**	**4.89**		**5.78**	**4.22**	**4.89**	**4.33**		**4.22**	**5.00**	**4.78**	**3.44**	

Factors	SE (d)	$CD_{(0.05)}$	*p*-Value	Factors	SE (d)	$CD_{(0.05)}$	*p*- value	Factors	SE (d)	$CD_{(0.05)}$	*p*-value
Temperature	0.52	1.07	0.012*	Temperature	0.63	1.29	0.042*	Temperature	0.51	1.05	0.001*
GA_3 concentration (G)	0.67	1.38s	0.000*	NAA conc. (N)	0.81	1.66	0.000*	Thiourea conc. (U)	0.66	1.35	0.000*
Interaction (T × G)	1.17	2.38	0.136 NS	Interaction(T × N)	1.40	2.87	0.221 NS	Interaction (T × U)	1.14	2.33	0.387 NS

$p \leq 0.05$ Significant (*); $p > 0.05$ Non-significant (NS).

Table 4. Effect of different temperatures and treatments on mean daily germination (number of seeds germinated per day)

Temperature (T)	Gibberellic acid concentration (G)						Naphthalene acetic acid (N)					Thiourea concentration (U)				
	Control	25 ppm	50 ppm	75 ppm	100 ppm	Mean	25 ppm	50 ppm	75 ppm	100 ppm	Mean	25 ppm	50 ppm	75 ppm	100 ppm	Mean
T_1 (15 °C)	0.04	0.26	0.28	0.19	0.31	0.22	0.17	0.18	0.19	0.23	0.16	0.18	0.23	0.21	0.24	0.18
T_2 (20 °C)	0.14	0.26	0.35	0.33	0.31	0.28	0.24	0.32	0.19	0.27	0.23	0.26	0.28	0.35	0.43	0.29
T_3 (25 °C)	0.03	0.15	0.30	0.15	0.19	0.16	0.14	0.31	0.08	0.07	0.13	0.23	0.10	0.09	0.34	0.16
Mean (concentration)	0.07	0.22	0.31	0.22	0.27		0.18	0.27	0.15	0.19		0.22	0.20	0.22	0.34	

Factors	SE (d)	CD (0.05)	*p*-value	Factors	SE (d)	$CD_{(0.05)}$	*p*-value	Factors	SE (d)	$CD_{(0.05)}$	*p*-value
Temperature (T)	0.03	0.05	0.001*	Temperature (T)	0.03	0.05	0.001*	Temperature (T)	0.03	0.07	0.001*
GA_3 concentration (G)	0.03	0.07	0.000*	NAA conc. (N)	0.03	0.07	0.000*	Thiourea conc. (U)	0.04	0.09	0.000*
Interaction (T × G)	0.06	0.12	0.520 NS	Interaction (T × N)	0.06	0.12	0.082 NS	Interaction (T × U)	0.08	0.15	0.304 NS

$p \leq 0.05$ Significant (S); $p > 0.05$ Non-significant (NS).

Germination percentage

Germination was significantly affected by both temperature and growth regulator treatments (Table 5). Maximum germination (64.67 %) was recorded under 20 °C with 50 ppm GA_3, followed by 63.33 % at 100 ppm GA_3. Among the growth regulators, GA_3 was most effective, with an overall mean germination of 46.67 %, while NAA and thiourea showed relatively lower means (27.11 and 44.89 %, respectively). Temperature also played a significant role, with 20 °C (T_2) recording the highest mean germination (45.47 % under GA_3, 35.73 % under NAA, 47.73 % under Thiourea). Pre-conditioning seed treatments with GA_3 has been shown to be an efficient method for releasing seeds from dormancy and increasing GR (25–27). This is because breaking the dormancy of the seeds only worked within a limited temperature range (28). This result might be due to temperature playing an important role in seed germination by affecting the metabolic processes involved in germination (29). These findings conform with those nitrogenous chemicals, such as thiourea, have been effectively linked to the enhancement of seed germination by breaking both innate and environmental seed dormancy (30, 31).

Germination energy

Similar trends were observed for GE (Table 6). The highest GE (24.00 %) was found at 20 °C with 50 ppm GA_3, followed by 23.33 % under 25 ppm NAA at the same temperature (20 °C). Thiourea treatments also enhanced GE, where maximum (22 %) was found at 100 ppm under 20 °C. Overall, GA_3 at 50 ppm was higher across all temperatures, yielding the maximum mean value (17.78 %).

Temperature is one of the most important environmental factors determining the success of germination and all seeds need proper temperature for germination. Generally, low temperature significantly delayed the germination (32). Pre-chilling, scarification and treatments with GA_3 or potassium nitrate (KNO_3) are the standard procedures used to enhance seed germination of dormant seeds (33). The results of the study are in agreement with the findings of a previous study (34). Amid different temperature regimes with response to NAA concentrations, maximum GE (14.93 %) was recorded at 20 °C, whereas the minimum GE (9.33 %) was recorded at 25 °C. Appropriate temperature is probably the most important factor in regulating germination (35). Thiourea at 1.0 % concentration resulted in the highest seed germination (89.00 %) in *Hippophae salicifolia*, whereas higher concentrations caused a significant decline in germination percentage. Similar trends have been reported earlier by several workers (9, 36, 37).

Rate of germination (seeds germinated per day)

The rate of germination, expressed as seeds germinated per day (Table 7), was maximum at 20 °C with 100 ppm thiourea (1.16), followed by 50 ppm GA_3 (0.85) and 50 ppm thiourea (1.05). Mean values among the concentrations revealed the superiority of GA_3 (0.67) and thiourea (0.73) over NAA (0.44). The minimum rate, GR, was consistently observed at 25 °C across all treatments. Gibberellic Acid can eliminate the natural chilling requirement for dormant seeds. The result of the interaction effect of temperature and GA_3 indicated that the maximum speed of germination (0.85 seeds day^{-1}) was in the treatment combination 20 °C × 50 ppm, while the minimum speed of germination (0.12 seeds day^{-1}) was in the treatment combination 25 °C × Control. The results of the study are in agreement with the findings of (38). Thiourea probably

Table 5. Effect of different temperature and treatments on germination per cent

Temperature (T)	Gibberellic acid concentration (G)					Naphthalene acetic acid (N)					Thiourea concentration (U)				
	Control	25 ppm	50 ppm	75 ppm	100 ppm	Mean	25 ppm	50 ppm	75 ppm	100 ppm	Mean	25 ppm	50 ppm	75 ppm	100 ppm	Mean
T_1 (15 °C)	13.33	38.00	62.67	42.67	47.33	**40.80**	38.33	36.67	42.00	37.33	**33.53**	45.33	44.00	36.67	49.33	**37.73**
T_2 (20 °C)	20.00	36.67	64.67	42.67	63.33	**45.47**	44.00	52.00	30.67	32.00	**35.73**	49.33	45.33	58.67	65.33	**47.73**
T_3 (25 °C)	9.33	28.00	32.00	26.67	29.33	**25.07**	18.67	18.67	14.67	12.00	**14.67**	40.00	26.67	21.33	30.00	**25.07**
Mean (concentration)	**14.22**	**34.22**	**53.11**	**37.33**	**46.67**		**33.37**	**35.78**	**29.11**	**27.11**		**44.89**	**38.67**	**38.89**	**48.22**	
Factors		**SE (d)**			**CD (0.05)**	***p*-value**		**Factors**		**SE (d)**	**CD (0.05)**	***p*-vale**		**Factors**		**SE (d)**	**CD (0.05)**	***p*-value**
Temperature (T)		2.82			5.79	0.000*	Temperature (T)		3.18	6.52	0.000*	Temperature (T)		3.36	6.89	0.000*
GA_3 concentration (G)		3.64			7.47	0.000*	NAA conc. (N)		4.10	8.42	0.000*	Thiourea conc. (U)		4.33	8.89	0.000*
Interaction (T × G)		6.31			12.94	0.034 NS	Interaction (T × N)		7.10	14.50	0.118 NS	Interaction (T × U)		7.50	15.32	0.034 NS

$p \leq 0.05$ Significant (*); $p > 0.05$ Non-significant (NS).

Table 6. Effect of different temperatures and treatments on germination energy per cent

Temperature (T)	Gibberellic acid concentration (G)						Naphthalene acetic acid (NAA)						Thiourea concentration (U)					
	Control	25 ppm	50 ppm	75 ppm	100 ppm	Mean	25 ppm	50 ppm	75 ppm	100ppm	Mean	2 5ppm	50 ppm	75 ppm	100 ppm	Mean		
T_1 (15 °C)	6.67	8.00	16.00	12.00	20.00	**12.53**	12.00	13.33	13.33	18.67	**12.80**	20.67	18.00	8.67	14.67	**13.73**		
T_2 (20 °C)	8.67	16.00	24.00	17.33	18.67	**16.93**	13.33	23.33	12.00	17.33	**14.93**	16.00	20.67	16.67	22.00	**16.80**		
T_3 (25 °C)	4.00	12.00	13.33	12.00	13.33	**10.93**	6.67	21.33	8.00	6.67	**9.33**	14.00	14.00	14.00	16.67	**12.53**		
Mean (concentration)	**6.44**	**12.00**	**17.78**	**13.78**	**17.33**		**10.67**	**19.33**	**11.11**	**14.22**		**16.89**	**17.56**	**13.11**	**17.78**			
Factors	**SE (d)**		**CD (0.05)**		***p*-value**	**Factors**	**SE (d)**	**CD (0.05)**	***p*-value**	**Factors**	**SE (d)**	**CD (0.05)**	***p*-value**					
Temperature (T)	1.95		4.00		0.013*	Temperature (T)	1.69	3.48	0.009*	Temperature (T)	1.14	2.34	0.002*					
GA_3 concentration (G)	2.52		5.17		0.001*	NAA conc. (N)	2.19	4.49	0.000*	Thiourea conc. (U)	1.47	3.03	0.000*					
Interaction (T × G)	4.36		8.91		0.703 NS	Interaction (T × N)	3.79	7.73	0.083 NS	Interaction(T × U)	2.55	5.24	0.023*					

$p \leq 0.05$ Significant (S); $p > 0.05$ Non-significant (NS).

Table 7. Effect of different temperatures and treatments on the speed of germination (seeds germinated per day)

Temperature (T)	Gibberellic acid concentration (G)						Naphthalene acetic acid (NAA)						Thiourea concentration (U)					
	Control	25 ppm	50 ppm	75 ppm	100 ppm	Mean	Control	25 ppm	50 ppm	75 ppm	100 ppm	Mean	Control	25 ppm	50 ppm	75 ppm	100 ppm	Mean
T_1 (15 °C)	0.20	0.46	0.81	0.49	0.73	**0.54**	0.20	0.34	0.70	0.45	0.39	**0.42**	0.20	0.52	0.53	0.50	0.54	**0.46**
T_2 (20 °C)	0.25	0.74	0.85	0.68	0.84	**0.67**	0.25	0.45	0.73	0.35	0.63	**0.48**	0.25	0.64	1.05	0.55	1.16	**0.73**
T_3 (25 °C)	0.12	0.21	0.36	0.29	0.30	**0.26**	0.12	0.19	0.19	0.14	0.30	**0.19**	0.12	0.33	0.38	0.32	0.49	**0.33**
Mean (concentration)	**0.19**	**0.47**	**0.67**	**0.49**	**0.62**		**0.19**	**0.33**	**0.54**	**0.31**	**0.44**		**0.19**	**0.50**	**0.65**	**0.46**	**0.73**	
Factors	**SE (d)**		**CD (0.05)**		***p*-value**	**Factors**	**SE (d)**	**CD (0.05)**	***p*-value**	**Factors**	**SE (d)**	**CD (0.05)**	***p*-value**					
Temperature (T)	0.09		0.18		0.000*	Temperature (T)	0.04	0.08	0.000*	Temperature (T)	0.06	0.13	0.000*					
GA_3 concentration (G)	0.11		0.23		0.002*	NAA conc. (N)	0.05	0.10	0.000*	Thiourea conc. (U)	0.08	0.16	0.000*					
Interaction (T × G)	0.20		0.40		0.809 NS	Interaction (T × N)	0.08	0.17	0.005*	Interaction (T × U)	0.14	0.28	0.034*					

$p \leq 0.05$ Significant (*); $p > 0.05$ Non-significant (NS).

inhibits RNA breakdown in the seed and also inhibits enzyme denaturation (39).

Shoot length

Shoot length (SL) was significantly increased by GA_3, the maximum SL (4.89 cm) was recorded at 20 °C with 50 ppm GA_3, followed by 4.52 cm at 100 ppm GA_3 (Table 8). Among NAA treatments, the maximum SL (4.81 cm) was found at 25 ppm at 20 °C, while thiourea at 100 ppm under the same temperature resulted in a SL of 5.21 cm, the highest across treatments. Gibberellic acid is also known to play an essential role in seed germination, stem elongation and flower development (40). In the treatment combination 20 °C × 50 ppm, the maximum SL (4.89 cm) was found, whereas the minimum SL (0.05 cm) was found in the treatment combination 25 °C × Control. It might be due to the fact that pre-sowing treatment with thiourea influences the duration of germination, seedling height, number of branches and roots (41, 42).

Root length

Root length (RL) (Table 9) showed significant variation. The maximum RL (3.50 cm) was obtained with 100 ppm Thiourea at 20 °C. Gibberellic acid at 50 ppm also promoted root growth (2.27 cm at 20 °C). In contrast, NAA treatments were found to be less effective, with mean values generally lower than GA_3 and thiourea. Given the importance of medicinal plants, understanding seed germination responses to temperature is agronomically important (43). The significance of plant growth regulators, particularly gibberellins in breaking seed dormancy and enhancement of seed germination have been studied extensively and is well established (44).

Temperature is one of the most important environmental factors determining the success of germination and all seeds need proper temperature for germination. Generally, low temperatures significantly delayed the germination (31). Many practices have been used to break seed dormancy, among which are dipping seeds in sulphuric acid of different concentrations to soften the hard seed coat and treatment with the plant hormone GA_3 (45), thiourea (46). The result of the interaction effect of temperature and thiourea indicated that maximum RL (3.50 cm) was in the treatment combination 20 °C × 100 ppm, while the minimum RL (0.27 cm) was in the treatment combination 25 °C × Control. The results of the study are in agreement with the findings of a previous study (47).

Seedling vigor index-I

A strong interaction between temperature and growth regulator was observed for seedling vigour (Table 10). The highest SVI (233.88) was recorded at 20 °C with 50 ppm thiourea, followed by 150.71 under 50 ppm GA_3 and 150.63 under 25 ppm NAA at 20 °C. Overall, thiourea exhibited the maximum mean vigour index (124.82), surpassing GA_3 (88.69) and NAA (86.95). The maximum seedling vigor index-I (150.71) was found in the treatment combination 20 °C × 50 ppm, while the lowest seedling vigor index-I (2.24) was found in the treatment combination 25 °C × Control. The results of the study are in agreement with the similar findings of (47). Appropriate temperature is probably the most important factor in regulating germination (34). In the case of thiourea, only the medium concentration showed better germination than the control (48, 49).

Table 8. Effect of different temperatures and chemicals on shoot length (cm)

Temperature	Gibberellic acid concentration					Naphthalene acetic acid					Thiourea concentration				
	Control	25 ppm	50 ppm	75 ppm	100 ppm	Mean	25 ppm	50 ppm	75 ppm	100 ppm	Mean	25 ppm	50 ppm	75 ppm	100 ppm	Mean
T_1 (15 °C)	0.63	3.41	4.21	1.39	4.25	**2.78**	0.27	2.64	0.10	2.61	**1.25**	2.70	3.40	2.64	2.61	**2.40**
T_2 (20 °C)	0.09	2.91	4.89	3.81	4.52	**3.25**	3.13	4.81	2.67	2.56	**2.65**	4.33	4.09	3.72	5.21	**3.49**
T_3 (25 °C)	0.05	2.31	2.58	2.41	2.52	**1.97**	0.30	1.70	0.40	0.89	**0.67**	2.48	2.59	1.91	2.60	**1.93**
Mean (concentration)	**0.26**	**2.88**	**3.90**	**2.54**	**3.77**		**1.23**	**3.05**	**1.06**	**2.02**		**3.17**	**3.36**	**2.76**	**3.47**	
Factors	**SE (d)**		**CD (0.05)**		***p*-value**		**Factors**		**SE (d)**	**CD (0.05)**	***p*-value**	**Factors**		**SE (d)**	**CD (0.05)**	***p*-value**
Temperature	0.27		0.56		0.000*		Temperature		0.23	0.47	0.000*	Temperature		0.23	0.46	0.000*
GA_3 concentration (G)	0.35		0.72		0.000*		NAA conc. (N)		0.29	0.60	0.000*	Thiourea conc. (U)		0.29	0.60	0.000*
Interaction (T × G)	0.61		1.24		0.008 NS		Interaction (T × N)		0.51	1.04	0.000*	Interaction (T× U)		0.51	1.04	0.012*

$p \leq 0.05$ Significant (*); $p > 0.05$ Non-significant (NS).

Table 9. Effect of different temperature and chemicals on root length (cm)

Temperature (T)	Gibberellic acid concentration (G)						Naphthalene acetic acid (NAA)						Thiourea concentration (U)					
	G_1 Control	G_2 25 ppm	G_3 50 ppm	G_4 75 ppm	G_5 100 ppm	Mean (T)	N_1 Control	N_2 25 ppm	N_3 50 ppm	N_4 75 ppm	N_5 100 ppm	Mean (T)	U_1 Control	U_2 25 ppm	U_3 50 ppm	U_4 75 ppm	U_5 100 ppm	Mean (T)
T_1 (15 °C)	0.36	1.71	1.70	1.49	1.75	**1.40**	0.36	1.85	1.89	0.53	0.43	**1.01**	0.36	1.77	1.74	1.75	2.09	**1.54**
T_2 (20 °C)	0.29	1.53	2.27	1.27	1.76	**1.42**	0.29	1.15	2.27	1.91	0.36	**1.20**	0.29	1.74	1.91	1.77	3.50	**1.84**
T_3 (25 °C)	0.27	0.91	1.48	0.69	1.79	**1.03**	0.27	1.04	0.56	0.42	0.53	**0.56**	0.27	1.10	2.43	1.20	1.07	**1.21**
Mean (concentration)	**0.30**	**1.38**	**1.81**	**1.15**	**1.77**		**0.30**	**1.35**	**1.57**	**0.95**	**0.44**		**0.30**	**1.54**	**2.03**	**1.57**	**2.22**	

Factors	SE (d)	$CD_{(0.05)}$	*p*-value	Factors	SE (d)	$CD_{(0.05)}$	*p*-value	Factors	SE (d)	$CD_{(0.05)}$	*p*-value
Temperature (T)	0.15	0.32	0.025*	Temperature (T)	0.09	0.18	0.000*	Temperature (T)	0.18	0.37	0.006*
GA_3 concentration (G)	0.20	0.41	0.000*	NAA conc. (N)	0.11	0.23	0.000*	Thiourea conc. (U)	0.23	0.48	0.000*
Interaction (T × G)	0.35	0.70	0.378 NS	Interaction (T × N)	0.20	0.40	0.000*	Interaction (T × U)	0.40	0.83	0.002*

$p \leq 0.05$ Significant (*); $p > 0.05$ Non-significant (NS).

Table 10. Effect of different temperatures and chemicals on seedling vigor index

Temperature (T)	Gibberellic acid concentration (G)						Naphthalene acetic acid (NAA)					Thiourea concentration (U)				
	Control	25 ppm	50 ppm	75 ppm	100 ppm	Mean (T)	25 ppm	50 ppm	75 ppm	100 ppm	Mean (T)	25 ppm	50 ppm	75 ppm	100 ppm	Mean (T)
T_1 (15 °C)	5.75	67.96	110.62	65.34	88.03	**67.54**	64.81	109.05	64.05	86.38	**66.01**	83.42	79.96	66.77	105.22	**68.23**
T_2 (20 °C)	5.77	60.87	150.71	59.63	118.15	**79.02**	61.09	150.63	58.48	116.19	**78.43**	94.03	89.53	106.36	233.88	**105.92**
T_3 (25 °C)	2.24	27.73	49.94	20.57	59.91	**32.08**	25.73	49.06	18.56	58.27	**30.77**	46.75	68.33	26.79	35.35	**35.89**
Mean (concentration)	**4.59**	**52.19**	**103.76**	**48.51**	**88.69**		**50.54**	**102.91**	**47.03**	**86.95**		**74.73**	**79.27**	**66.64**	**124.82**	

Factors	SE (d)	$CD_{(0.05)}$	*p*-value	Factors	SE (d)	$CD_{(0.05)}$	*p*-value	Factors	SE (d)	$CD_{(0.05)}$	*p*-value
Temperature (T)	8.89	18.25	0.000*	Temperature (T)	8.81	18.08	0.000*	Temperature (T)	9.41	19.31	0.000*
GA_3 concentration (G)	11.48	23.56	0.000*	NAA conc. (N)	11.37	23.34	0.000*	Thiourea conc. (U)	12.15	24.93	0.000*
Interaction (T × G)	19.88	40.60	0.101 NS	Interaction (T × N)	19.70	40.22	0.097 NS	Interaction (T × U)	21.04	43.17	0.000*

$p \leq 0.05$ Significant (*); $p > 0.05$ Non-significant (NS).

Conclusion

Early germination and subsequent seedling growth were strongly affected by both temperature and the applied chemical treatments. Among the tested temperature levels, 20 °C (T_2) was the most favourable, resulting in higher germination percentage, faster germination, greater GE and improved seedling vigor. In comparison, lower (15 °C) and higher (25 °C) temperatures significantly reduced these parameters. Regarding chemical applications, GA_3 at 50 ppm, NAA at 50 ppm and thiourea at 100 ppm consistently performed better than other treatments.

The combination of GA_3 at 50 ppm with 20 °C produced the highest vigor index values (>150), maximum germination and longer shoots and roots. Thus, the use of GA_3 at 50 ppm under 20 °C conditions is recommended for improving germination and seedling vigor in the studied species. These results highlight that successful early growth and nursery establishment depend on the interaction between an optimal regulator concentration and a moderate temperature. Application of growth regulators significantly enhanced germination traits, with thiourea at 100 ppm emerging as the most effective treatment across all observations, including germination percentage, GE, germination speed, seedling growth and vigor index. The overall best performance occurred under the treatment combination 20 °C × thiourea 100 ppm, which hastened germination, promoted seedling growth and produced more vigorous seedlings than other treatments. This suggests that thiourea effectively helps break seed dormancy and stimulates metabolic processes required for rapid germination. However, because only a few concentrations were evaluated, further studies are needed to determine the maximum safe level of thiourea before inhibitory effects become apparent. In conclusion, maintaining seeds at 20 °C and treating them with thiourea at 100 ppm can be recommended as a practical protocol for enhancing germination and seedling establishment in *C. carvi*.

Acknowledgements

The authors would like to thank the VCSG Uttarakhand University of Horticulture and Forestry for their support in providing databases for this study.

Authors' contributions

ASB and PS designed the experiments, conceptualised the study and handled writing, review and editing. SBK, UBP and BL conducted the literature search. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflicts of interest to declare.

Ethical issues: None

References

1. Medani RA, Taha RS. Improving growth and yield of caraway (*Carum carvi* L.) plants by decapitation and/or active dry yeast application. Int J Curr Microbiol Appl Sci. 2015;4(9):47–60.
2. Dev S. *Carum carvi*. In: Prime Ayurvedic Plant Drugs. Cham: Springer; 2023. p. 212–17. https://doi.org/10.1007/978-3-031-22075-3_28
3. Sachan AK, Das DR, Kumar M. *Carum carvi* – An important medicinal plant. J Chem Pharm Res. 2016;8(3):529–33.
4. Malhotra SK. Caraway. In: Peter KV, editor. Handbook of herbs and spices. 2nd ed. Cambridge: Woodhead Publishing; 2012. p. 225–48. https://doi.org/10.1533/9780857095688.225
5. Bradley PR, editor. British herbal compendium: a handbook of scientific information on widely used plant drugs. Vol. 2. Bournemouth: British Herbal Medicine Association; 1992.
6. Laribi B, Bettaieb I, Kouki K, Sahli A, Mougou A, Marzouk B. Water deficit effects on caraway (*Carum carvi* L.) growth, essential oil and fatty acid composition. Ind Crops Prod. 2009;30(3):372–9. https://doi.org/10.1016/j.indcrop.2009.07.005
7. Bisht AS, Sati M, Rana S, Chauhan RS. Effect of light vs dark on seed germination of *Hedychium spicatum* Smith. Int J Med Plants Nat Prod. 2015;1(1):29–30.
8. Samojlik I, Lakic N, Mimica-Dukic N, Djakovic-Svajcer K, Bozin B. Antioxidant and Hepatoprotective Potential of Essential Oils of Coriander (*Coriandrum sativum* L.) and Caraway (*Carum carvi* L.) (Apiaceae). J Agric Food Chem. 2010;58(15):8848–53. https://doi.org/10.1021/jf101645n
9. Gupta A, Dubey M, Parmar M, Mahajan S, Sharma R. Evaluation of antimicrobial activity of *Carum carvi* seed extract against *Escherichia coli* and *Aspergillus niger*. Drug Invent Today. 2011;3:211–3.
10. Şanli A, Karadoan T, Tonguç M, Baydar H. Effects of caraway (*Carum carvi* L.) seed on sprouting of potato (*Solanum tuberosum* L.) tubers under different temperature conditions. Turk J Field Crops. 2010;15 (1):54–8.
11. Wêglarz Z. Production of biennial caraway for seed and essential oil. In: Németh E, editor. Caraway: the genus Carum. London: CRC Press; 1999.
12. Tzortzakis NG. Effect of pre-sowing treatment on seed germination and seedling vigour in endive and chicory. Hortic Sci (Prague). 2009;36(3):117–25. https://doi.org/10.17221/28/2008-HORTSCI
13. Galambosi B, Peura P. Agrobotanical features and oil content of wild and cultivated forms of caraway (*Carum carvi* L.). J Essent Oil Res. 1996;8(4):389–97. https://doi.org/10.1080/10412905.1996.9700646
14. Nyachiro JM, Clarke FR, DePauw RM, Knox RE, Armstrong KC. Temperature effects on seed germination and expression of seed dormancy in wheat. Euphytica. 2002;126:123–7. https://doi.org/10.1023/A:1019694800066
15. Oliveira AKM, Ribeiro JWF, Pereira KCL, Silva CAA. Effects of temperature on the germination of *Diptychandra aurantiaca* (Fabaceae) seeds. Acta Sci Agron. 2013;35(2):203–8. https://doi.org/10.4025/actasciagron.v35i2.15977
16. Francis DV, Subhan A, Mourad AH, Abdalla AK, Ahmed ZFR. Optimizing germination conditions of ghaf seed using ZnO nanoparticle priming through Taguchi method analysis. Sci Rep. 2024;14(1):15946. https://doi.org/10.1038/s41598-024-67025-6
17. Trivedi V, Rao K, Sasidharan N, Patel DA. Influence on seed quality parameters under different temperature and artificial ageing treatment in cumin (Cuminum cyminum). Indian J Agric Sci. 2023;88(1):121–4. https://doi.org/10.56093/ijas.v88i1.79637
18. Hassanpouraghdam M, Hajisamadi AB, Khalighi A. Gibberellic acid foliar application influences growth, volatile oil and some physiological characteristics of coriander (*Coriandrum sativum* L.). Rom Biotechnol Lett. 2011;16(4): 6322–27.
19. Hassan FA, Alshamsi ASM, Alyafei MAS, Kurup S, Al Busaidi N, Ahmed ZFR. Enhancing germination of ghaf seeds (*Prosopis cineraria* L.) using sulfuric acid scarification and cytokinin. Acta Hortic. 2023;1365:39–44. https://doi.org/10.17660/ActaHortic.2023.1365.5

20. Ali HMH, Sallam DAHM. Inducing the growth and flowering of caraway (*Carum carvi* L.) plant. J Appl Biol Biotechnol. 2022;10(4):86–91. https://doi.org/10.7324/JABB.2022.100412

21. Synge PM. Dictionary of gardening: a practical and scientific encyclopedia of horticulture. 2nd ed. Oxford: Clarendon Press; 1974.

22. Czabator FJ. Germination value: an index combining speed and completeness of pine seed germination. For Sci. 1962;8(4):386–96. https://doi.org/10.1093/forestscience/8.4.386

23. Abdul-Baki AA, Anderson JD. Vigor determination in soybean seed by multiple criteria. Crop Sci. 1973;13(6):630–3. https://doi.org/10.2135/cropsci1973.0011183X001300060013x

24. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. New York: John Wiley and Sons; 1984.

25. Belwal T, Bisht A, Bhatt ID, Rawal RS. Influence of seed priming and storage time on germination and enzymatic activity of selected *Berberis* species. Plant Growth Regul. 2015;77:189–99. https://doi.org/10.1007/s10725-015-0051-0

26. Kumar S, Malik TP, Mor VS, Kumar P. Effect of gibberellic acid on seed quality of coriander (*Coriandrum sativum* L.). J Pharmacogn Phytochem. 2018;7:830–2. https://doi.org/10.20546/ijcmas.2018.709.318

27. Shah SH. Physiological effects of pre-sowing seed treatment with gibberellic acid on *Nigella sativa* L. Acta Bot Croat. 2007;66(1):67–73.

28. Ghaseemi M, Puteh AB, Sinniah UR, Wahab ZB. Effect of different temperature regimes on seed germination in Bunium persicum (black zira or black cumin) ecotypes. Int J Agric Res Rev. 2012;2(3):240–6.

29. Verma SK, Kumar B, Ram G, Singh HP, Lal RK. Varietal effect on germination parameters at controlled and uncontrolled temperature in palmarosa (*Cymbopogon martini*). Ind Crops Prod. 2010;32(3):696–9. https://doi.org/10.1016/j.indcrop.2010.07.015

30. Aldasoro JJ, Matilla A, Nicolas G. Effect of ABA, fusicoccin and thiourea on germination and K+ and glucose uptake in chickpea seeds at different temperatures. Plant Physiol. 1981;53(2):139–45. https://doi.org/10.1111/j.1399-3054.1981.tb04123.x

31. El-Keblawy A, Gairola S. Dormancy regulating chemicals alleviate innate seed dormancy and promote germination of desert annuals. J Plant Growth Regul. 2016;36:300–11. https://doi.org/10.1007/s00344-016-9640-z

32. Pourreza J, Bahrani A. Estimating cardinal temperatures of milk thistle (*Silybum marianum*) seed germination. Am Eurasian J Agric Environ Sci. 2012;12(11):1485–9.

33. Bhardwaj AK, Kapoor S, Naryal A, Bhardwaj P, Warghat AR, Kumar B, et al. Effect of various dormancy breaking treatments on seed germination, seedling growth and seed vigour of medicinal plants. Trop Plant Res. 2016;3(3):508–16. https://doi.org/10.22271/tpr.2016.v3.i3.067

34. Ünver MC, Tilki F. Salinity, germination promoting chemicals, temperature and light effects on seed germination of Anethum graveolens L. Bulg J Agric Sci. 2012;18(6):974–80.

35. Nerson H. Seed production and germinability of cucurbit crops. Seed Sci Biotechnol. 2007;1(1):1–10.

36. Pandey H, Nandi SK, Nadeem M, Palni LMS. Chemical stimulation of seed germination in *Aconitum heterophyllum* Wall. and *Aconitum balfouri* Stapf. Seed Sci Technol. 2000;28(1):39–48.

37. Bhatt R, Shetty GR, Rajasekharan PE, Pooja DA, Ganapathi M, Nadukeri S. Effect of pre-sowing seed treatments on *Aristolochia tagala* Cham. Int J Curr Microbiol Appl Sci. 2020;9(10):1803–8. https://doi.org/10.20546/ijcmas.2020.910.219

38. Elhindi KM, Dewir YH, Asrar AW, Abdel-Salam E, El-Din AS, Ali M. Improvement of seed germination in three medicinal plant species by plant growth regulators. HortScience. 2016;51(7):887–91. https://doi.org/10.21273/HORTSCI.51.7.887

39. Anandhi S, Rajamani K. Studies on seed germination and growth in *Gloriosa superba* L. Global J Res Med Plants & Indigen Med. 2012;1(10):524–28.

40. Sharma RK, Sharma S, Sharma SS. Seed germination behavior of some medicinal plants of Lahaul and Spiti cold desert (Himachal Pradesh): implications for conservation and cultivation. Curr Sci. 2006;90(8):1113–8.

41. Dhankar DS, Singh M. Seed germination and seedling growth in aonla (*Phyllanthus emblica* Linn.) as influenced by gibberellic acid and thiourea. Crop Res Hisar. 1996;12(3):363–6.

42. Singh DK, Bhattacharya B, Mondal K. Role of pre-sowing seed treatments with different chemicals on germination behavior and seedling growth of jackfruit (*Artocarpus heterophyllus* Lam.). Environ Ecol. 2002;20(3):741–3.

43. Alipoor Z, Mahmodi S. Effect of different temperature on germination properties of fennel (*Foeniculum vulgare* Mill.), cannabis (*Cannabis sativa* L.) and sesame (*Sesamum indicum* L.). Iran J Seed Res. 2015;2(1):37–50.

44. Thakur A, Thakur PS, Dutt V, Thakur CL. Conservation of *Podophyllum hexandrum*: an endangered medicinal herb through seeds. Indian J Plant Physiol. 2010;15(2):110–6.

45. Abdalla ST, Mckelvie AD. The interaction of chilling and gibberellic acid on the germination of seeds of ornamental plants. Seed Sci Technol. 1980;8:139–44.

46. Yadav P, Srivastava S. Effect of thiourea application on root, old leaf and young leaf of two contrasting rice varieties (*Oryza sativa* L.) grown in arsenic contaminated soil. Environ Technol Innov. 2021;21:101368. https://doi.org/10.1016/j.eti.2021.101368

47. Thakur A, Sayal N. Effects of seed invigoration treatments on seed germination, seedling vigour and physio-biochemical characteristics of *Angelica glauca* Edgew. Int J Bioresour Stress Manag. 2018;9(3):353–8. https://doi.org/10.23910/IJBSM/2018.9.3.3C0640

48. Butola JS, Pant S, Samant SS. Effect of pre-sowing seed treatments in *Hypericum perforatum* L. Seed Res. 2007;35(2):205–209.

49. Bisht AS, Nautiyal BP, Bhatt AB. Propagation and growth performance of *Hedychium spicatum* Smith under different hormonal and soil treatments. Indian Forester. 2009;135(1):60–6.

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.