



Check for updates



Research Article

Optimizing Garlic Growth: Influence of Vernalization and Photoperiod on Sprouting and Biomass Accumulation

Maira Raqeeb Tunio¹, Tanveer Fatima Miano^{1*}, Muzafaruddin Chachar^{1*}, Ghulam Fatima Tunio¹, Aaqib Mustafa¹, Ghulam Rasool Tunio², Shahmeer Khan Tunio³, Memoona Islam Majeedano¹, Sana Shazia Jiskani^{1,4}

¹Department of Horticulture, Faculty of Crop Production, Sindh Agriculture University Tandojam, Pakistan.

²Department of Soil Science, Faculty of Crop Production, Sindh Agriculture University Tandojam, Pakistan.

³Vegetable Research Sub Station, Husri, Hyderabad, Pakistan.

⁴National Key Laboratory for Germplasm Innovation & Utilization of Horticultural Crops, Huazhong Agricultural University, Wuhan, China.

ABSTRACT

Garlic (*Allium sativum*) production is often constrained by poor sprouting and weak vegetative growth, which are strongly influenced by environmental cues such as temperature and day length. The present experiment was conducted during autumn 2022-23 at the Nursery, Department of Horticulture, Sindh Agriculture University Tandojam, to evaluate the effect of vernalization and photoperiod on the sprouting and early growth of garlic variety Desi at the green stage. The experiment followed a Completely Randomized Design (CRD) with a factorial arrangement comprising vernalization treatments ($V_1 = 5\text{ }^\circ\text{C} + 24\text{ h}$, $V_2 = 5\text{ }^\circ\text{C} + 48\text{ h}$, $V_3 = 7\text{ }^\circ\text{C} + 24\text{ h}$ and $V_4 = 7\text{ }^\circ\text{C} + 48\text{ h}$) and photoperiods ($P_1 = \text{Partial shade}$ and $P_2 = \text{Sunlight}$). Data were recorded for sprouting percentage, days to sprouting, plant height, leaves per plant, leaf length, leaf weight, fresh biomass, and days to harvest. Vernalization and photoperiod significantly influenced most growth attributes. Cloves treated at $7\text{ }^\circ\text{C}$ for 24 h or 48 h generally showed improved performance across sprouting and vegetative parameters. Specifically, $7\text{ }^\circ\text{C}$ for 24 h promoted early sprouting and higher leaf weight, while $7\text{ }^\circ\text{C}$ for 48 h produced longer leaves and greater fresh biomass. Plants grown under sunlight exhibited superior plant height and biomass compared to partial shade. The interaction of $7\text{ }^\circ\text{C}$ treatments with sunlight yielded the most vigorous plants overall. In conclusion, short- to moderate-duration vernalization ($7\text{ }^\circ\text{C}$ for 24-48 h) significantly enhanced sprouting and vegetative growth of garlic, with photoperiod playing a decisive role in optimizing these responses.

Keywords: Biomass, Garlic, Growth, Photoperiod, Sprouting, Vernalization

INTRODUCTION

Garlic (*Allium sativum*) is one of the oldest cultivated crops, valued for both culinary and medicinal purposes for thousands of years. Belonging to the Alliaceae family, it is closely related to onion, leek, and shallot, and has been widely cultivated across Central Asia, the Mediterranean, and later introduced to Europe, Africa, and America (Singh *et al.*, 2008; Chachar *et al.*, 2024). Its unique taste, smell, and phytochemicals have made it versatile across the world, whereas its medicinal values have been employed in the treatment of diseases like infections, heart diseases, and gastrointestinal disorders (Tattelman *et al.*, 2005; Chen *et al.*, 2009; Kuete, 2017). Garlic extracts have shown to have antioxidant, antimicrobial, antihypertensive and cholesterol-lowering activities which are mainly on account of the sulfur-containing factors including allicin (Khoo *et al.*, 2009).



*Correspondence

Tanveer Fatima Miano
tfmiano@sau.edu.pk
Muzafaruddin Chachar
muzafar_mkc@yahoo.com

Article History

Received: August 24, 2025
Accepted: October 07, 2025
Published Online: October 10, 2025

Cite this article

Tunio, M. R., Miano, T. F., Chachar, M., Tunio, G. F., Mustafa, A., Tunio, G. R., Tunio, S. K., Majeedano, M. I., & Jiskani, S. S. (2025). Optimizing garlic growth: Influence of vernalization and photoperiod on sprouting and biomass accumulation. *Integrative Plant Biotechnology*, 3, 281-289.



Copyright: © 2025 by the authors.
Licensee: Roots Press, Rawalpindi, Pakistan.

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license:
<https://creativecommons.org/licenses/by/4.0>

This versatile use has made it a globally demanded crop due to its economic and nutritional value. Environmental factors (mainly temperature and photoperiod) are very important to the growth and bulb development, and reproductive success of garlic. Vernalization, the exposure of plants or propagules to low temperatures in order to induce flowering, is a vital component of garlic physiology (Ritz *et al.*, 2010). Vernalization can be performed on seeds (e.g. wheat, spinach, and radish) or on plants with green tissues (e.g., garlic, onion and celery) depending on the species (Wu *et al.*, 2015). Garlic is a biennial plant of the green-plant type that needs cold treatment to bolt and initiate reproductive processes, and both temperature and age of plants play a decisive role (Dong *et al.*, 2013; Michael *et al.*, 2018). The vernalization process not only enables floral induction but does enable farmers to manipulate crop cycles to obtain off-season production (Mallah *et al.*, 2025). Research indicated that dormancy can be broken, and vegetative growth supported, via vernalization that occurs within 5-10 °C (Amasino, 2004). Inadequate chilling can lead to a postponement or inhibition of flowering thus lowering yield (Michaels *et al.*, 2003).

In addition to vernalization, photoperiod acts as a vital environmental cue regulating garlic growth and development. Photoperiod sensitivity in garlic influences sprouting, bulb initiation, and flowering, with long days generally promoting bulb enlargement and floral stalk elongation (Kamenetsky *et al.*, 2004; Brewster, 2008). Light perception is mediated by phytochromes and cryptochromes, which regulate hormonal pathways such as gibberellins that drive florogenesis (King *et al.*, 2006; Chia and Kubota, 2010). Prolonged exposure to long days enhances bulb formation and accelerates floral stalk elongation; however, excessively extended photoperiods may interfere with normal flower differentiation, leading to the development of topsets instead of flowers (Kamenetsky *et al.*, 2004; Mathew *et al.*, 2011). Temperature and photoperiod are synergistic where elevated temperatures and long day periods enhance bulb maturation, but short days and cool temperatures increase vegetative growth resulting in a delayed initiation of bulbs (Etoh *et al.*, 2002; Atif *et al.*, 2019).

Environmental manipulations with day length and temperature have also served the purposes of boosting garlic yields and fine-tuning its reproductive physiology (Kamenetsky *et al.*, 2007). e.g. vernalization and long days at high temperatures enhance bulb formation, production, and quality (Wu *et al.*, 2015). Photosynthetic efficiency, internode elongation, and leaf size are also morphological responses to light quality and quantity (Johkan *et al.*, 2011; Fan *et al.*, 2013). Blue light promotes leaf area growth, and red-orange light speeds up stem elongation and biomass deposition (Yang *et al.*, 2012). Additionally, shading condition and light microclimate also change considerably the physiology of garlic, due to temperature, humidity and carbon dioxide availability, which impact sprouting and the general growth (Cai, 2011; Song *et al.*, 2012). Collectively, these findings indicate that vernalization and photoperiod are the most important environmental factors that induce sprouting, bolting, and bulb development in garlic. Photoperiod and vernalization have different functions, although similar situations arise where photoperiod promotes flowering before vernalization can do so. The interplay of these factors is central to ensuring optimal garlic production in varying climatic conditions and the minimization of issues related to sterility, poor yields, and off-season use. This study, therefore, aims to evaluate the effect of vernalization and photoperiod on sprouting and growth of garlic (*Allium sativum* L.), providing insights into the environmental regulation of its developmental physiology.

MATERIALS AND METHODS

The present research was undertaken in autumn 2022-23 at the SAU Nursery Department of Horticulture, Sindh Agriculture University, Tandojam to investigate the effect of vernalization and photoperiod on sprouting and growth of Garlic (*Allium sativum*) at the green stage. Variety “Desi” sown in pots. Further details of the experiment are as follows:

Experimental design and Treatments

The experiment was conducted using a Completely Randomized Design (CRD) arranged in a factorial pattern with three replications. The study comprised two factors: vernalization period (Factor A) and photoperiod (Factor B). Factor A included four levels of vernalization ($V_1 = 5\text{ °C} + 24\text{ h}$, $V_2 = 5\text{ °C} + 48\text{ h}$, $V_3 = 7\text{ °C} + 24\text{ h}$, $V_4 = 7\text{ °C} + 48\text{ h}$) while Factor B comprised two photoperiod conditions ($P_1 =$ Partial shade and $P_2 =$ Sunlight).

The sunlight condition (P_2) represented open-field natural daylight with an average light intensity of approximately 65,000–70,000 lux (equivalent to 1,000–1,200 $\mu\text{mol m}^{-2}\text{ s}^{-1}$ PAR). The partial shade condition (P_1) was maintained under a 50% green shade net, reducing incident light intensity to about 30,000–35,000 lux ($\approx 400\text{--}500\text{ }\mu\text{mol m}^{-2}\text{ s}^{-1}$ PAR). These values are consistent with typical light levels reported for shaded and unshaded horticultural environments (Li and Kubota, 2009; Rajasekar *et al.*, 2013).

Planting and Maintenance

Garlic cloves were planted at a depth of 5 cm in each pot. Routine cultural practices such as weeding were performed as needed to ensure optimal growth conditions. Adequate irrigation was provided using tap water.

Observations and Measurements of Different Parameters

The growth parameters were measured as given in the following. The cloves of each treatment were periodically observed for sprouting. The number of days to sprouting was calculated from the date of sowing until the emergence of shoots from the cloves. The sprouting percentage for each treatment was estimated according to the method described by Islam *et al.* (2024) using the following formula:

$$\text{Cloves sprouting (\%)} = \frac{\text{Number of sprouted cloves}}{\text{Total number of planted cloves}} \times 100$$

The length of leaves (cm) was measured from the tip to the base of the lowest leaflet where it joins the leaf stem. Measurements were taken from five randomly selected plants per treatment in each replication, and the mean value was calculated for each treatment. Leaves per plant: The number leaves per plant was determined by counting the total leaves from five randomly selected plants per treatment in each replication, and the average value was calculated for each treatment. Plant height (cm) was measured from the neck to the tip of the tallest leaf using a measuring tape. Measurements were taken from five randomly selected plants per treatment in each replication, and the average value was calculated for each treatment.

Fresh biomass (g) was determined by weighing whole plants immediately after harvest using an electronic balance. The recorded weight included the inherent water content of the plants. Data were collected from five randomly selected plants per treatment in each replication, and mean values were calculated. Leaf weight (g) was measured by weighing all leaves from five randomly selected plants per treatment in each replication using an electronic balance. The average value for each treatment was then computed. Days to harvest were recorded when the plants reached full vegetative maturity, indicated by the thickening of the neck region. At this stage, the entire plants were harvested at the green mature leaf stage.

Statistical Analysis

The data were statistically analyzed using Statistix 8.1 software (Statistix, 2006). Analysis of variance (ANOVA) was performed to determine the significance of treatment effects, and the least significant difference (LSD) test at the 5% probability level was applied only when ANOVA indicated significant differences among treatments.

RESULTS

The results regarding the influence of vernalization and photoperiod on the sprouting and vegetative growth of garlic (*Allium sativum* L.) are presented in Tables 1–4.

Days to Sprouting

The data related to days to sprouting of garlic are presented in Table 1. The analysis of variance showed that vernalization and the interaction between vernalization and photoperiod significantly influenced the number of days to sprouting ($P < 0.05$), whereas the effect of photoperiod alone was non-significant ($P > 0.05$). With respect to vernalization, the maximum days to sprouting (9.24 days) were recorded at 5 °C for 48 h, followed by 8.33 days at 7 °C for 24 h.

The minimum days to sprouting (6.31 days) were observed when cloves were vernalized at 7 °C for 48 h. On average, cloves vernalized at 5 °C took longer (8.56 days) to sprout compared to 7 °C (7.72 days). Regarding the photoperiod effect, cloves exposed to partial shade took more time to sprout (8.56 days) compared to those under sunlight (6.79 days). The interactive effect of vernalization and photoperiod indicated that the longest sprouting period (9.88 days) occurred under 5 °C for 48 h in partial shade, whereas the shortest period (5.49 days) was observed under 7 °C for 48 h in sunlight. These results suggest that higher vernalization duration under low temperature delayed sprouting, while sunlight exposure under 7 °C for 48 h promoted early sprouting.

Cloves Sprouting (%)

The data related to clove sprouting percentage of garlic are presented in Table 1. Analysis of variance revealed that vernalization, photoperiod, and their interaction had non-significant effects on clove sprouting percentage ($P > 0.05$). Numerically, cloves vernalized at 5 °C for 24 h exhibited the highest sprouting percentage (75.42%), followed by 7 °C for 24 h (72.57%), while the lowest value (50.33%) was recorded at 7 °C for 48 h. On average, cloves vernalized at 5 °C showed slightly higher sprouting (67.74%) compared to those at 7 °C (61.45%). Similarly, cloves under partial shade (65.25%) and sunlight (63.93%) produced comparable sprouting percentages, indicating little influence of photoperiod. Although no statistically significant differences were detected, numerical trends suggest that shorter vernalization durations (24 h) tended to produce marginally higher sprouting compared with extended durations (48 h), regardless of photoperiod.

Table 1. Days to sprouting and cloves sprouting (%) of garlic under vernalization and photoperiod.

Vernalization temperature + Time Periods	Days to sprouting			Cloves sprouting percentage (%)		
	Photoperiod		Mean	Photoperiod		Mean
	Partial Shade	Sunlight		Partial Shade	Sunlight	
5 °C + 24 h	8.12 c	5.55 e	6.83 c	70.34	80.50	75.42
5 °C + 48 h	9.88 a	8.60 c	9.24 a	70.00	50.11	60.05
7 °C + 24 h	9.11 b	7.55 c	8.33 b	70.14	75.00	72.57
7 °C + 48 h	7.13 d	5.49 e	6.31 d	50.55	50.12	50.33
Mean	8.56	6.79		65.25	63.93	
<i>Level of Significance</i>	<i>Vernalization (V)</i>	<i>Photoperiod (P)</i>	<i>P x V</i>	<i>Vernalization (V)</i>	<i>Photoperiod (P)</i>	<i>P x V</i>
SE	0.4677	0.3307	0.6614	6.6144	4.6771	9.3541
LSD @ 5%	1.5253	1.0785	2.1571	21.570	15.252	30.505
Probability	0.0176	0.0650	0.0345	0.1079	0.7153	0.4803

Whereas LSD=Least significant difference

Table 2. Leaf length (cm) and Leaves per plant of garlic under vernalization and photoperiod.

Vernalization temperature + Time Periods	Leaf length (cm)			Leaves per plant		
	Photoperiod		Mean	Photoperiod		Mean
	Partial Shade	Sunlight		Partial Shade	Sunlight	
5 °C + 24 h	18.77	26.00	22.38 c	11.00	22.00	16.50
5 °C + 48 h	20.61	24.00	22.30 d	14.50	20.00	18.25
7 °C + 24 h	23.27	27.83	25.55 b	13.00	24.00	18.50
7 °C + 48 h	24.22	29.00	26.61 a	12.00	23.50	17.75
Mean	21.71 b	26.70 a		12.62 b	22.37 a	
<i>Level of Significance</i>	<i>Vernalization (V)</i>	<i>Photoperiod (P)</i>	<i>P x V</i>	<i>Vernalization (V)</i>	<i>Photoperiod (P)</i>	<i>P x V</i>
SE	0.8265	0.5844	1.1688	1.0155	0.7181	1.4361
LSD @ 5%	2.6953	1.9058	3.8117	3.3117	2.3418	4.6835
Probability	0.0122	0.0003	0.4611	0.2881	0.0000	0.3357

Whereas LSD=Least significant difference

Table 3. Plant height (cm) and fresh biomass of plant of garlic under vernalization and photoperiod.

Vernalization temperature + Time Periods	Plant height (cm)			Fresh biomass of plant		
	Photoperiod		Mean	Photoperiod		Mean
	Partial Shade	Sunlight		Partial Shade	Sunlight	
5 °C + 24 h	31.50	35.00	33.25	7.38	8.89	8.13
5 °C + 48 h	27.00	34.50	30.75	5.82	8.35	7.08
7 °C + 24 h	24.00	39.50	31.75	5.92	9.29	7.60
7 °C + 48 h	28.00	36.55	33.77	7.77	8.85	8.31
Mean	27.62 b	36.38 a		6.72 b	8.84 a	
<i>Level of Significance</i>	<i>Vernalization (V)</i>	<i>Photoperiod (P)</i>	<i>P x V</i>	<i>Vernalization (V)</i>	<i>Photoperiod (P)</i>	<i>P x V</i>
SE	1.7093	1.2087	2.417	0.6158	0.4354	0.870
LSD @ 5%	5.5744	3.9417	7.883	2.0081	1.4199	2.839
Probability	0.5833	0.0006	0.177	0.2685	0.0040	0.696

Whereas LSD=Least significant difference

Table 4 . Leaf weight (g) and days to harvest at green stage of garlic under vernalization and photoperiod.

Vernalization temperature + Time Periods	Leaf weight (g)			Days to harvest at green stage		
	Photoperiod		Mean	Photoperiod		Mean
	Partial Shade	Sunlight		Partial Shade	Sunlight	
5 °C + 24 h	2.77	3.53	3.15	90.00 d	92.00 c	91.00 b
5 °C + 48 h	2.28	3.14	2.71	92.00 c	88.00 e	90.00 c
7 °C + 24 h	2.21	4.26	3.23	93.00 b	85.00 g	89.00 d
7 °C + 48 h	2.31	3.94	3.12	96.00 a	87.00 f	91.50 a
Mean	2.39 b	3.71 a		92.75 a	88.00 b	
<i>Level of Significance</i>	<i>of Vernalization (V)</i>	<i>Photoperiod (P)</i>	<i>P x V</i>	<i>Vernalization (V)</i>	<i>Photoperiod (P)</i>	<i>P x V</i>
SE	0.2710	0.1916	0.3833	1.3130	0.9286	1.8572
LSD @ 5%	0.8846	0.4419	1.1389	4.0558	2.1411	5.7532
Probability	0.2525	0.0001	0.1358	0.0000	0.0000	0.0000

Whereas LSD=Least significant difference

Leaf Length (cm)

The data related to leaf length (cm) of garlic are presented in Table 2. The analysis of variance showed that vernalization and photoperiod significantly influenced leaf length ($P < 0.05$), whereas the interaction between the two factors was non-significant ($P > 0.05$). With respect to vernalization, the maximum leaf length (26.61 cm) was observed at 7 °C for 48 h, followed by 25.55 cm at 7 °C for 24 h. The minimum leaf length (22.30 cm) was recorded at 5 °C for 48 h, which was statistically similar to 22.38 cm under 5 °C for 24 h. On average, garlic cloves vernalized at 7 °C produced longer leaves compared to those treated at 5 °C. Regarding photoperiod, plants exposed to sunlight produced significantly longer leaves (26.70 cm) compared to those under partial shade (21.71 cm). The interactive effect of vernalization and photoperiod was found to be statistically non-significant. However, numerically the longest leaves (29.00 cm) were recorded at 7 °C for 48 h in sunlight, while the shortest (18.77 cm) were observed at 5 °C for 24 h in partial shade.

Leaves per Plant

The data related to garlic leaves per plant are presented in Table 2. The analysis of variance demonstrated that photoperiod had a highly significant effect ($P < 0.05$), while vernalization and the interaction between vernalization and photoperiod were statistically non-significant ($P > 0.05$). For vernalization, cloves subjected to 7 °C for 24 h produced the highest number of leaves per plant (18.50), followed by 18.25 leaves at 5 °C for 48 h. The lowest number of leaves (16.50) was observed at 5 °C for 24 h. On average, vernalization at 7 °C slightly enhanced leaf production compared to 5 °C.

Concerning the photoperiod, plants grown under sunlight produced significantly more leaves (22.37) than those under partial shade (12.62). The interactive effect of vernalization and photoperiod was non-significant. Nevertheless, the maximum number of leaves (24.00) was recorded at 7 °C for 24 h in sunlight, whereas the minimum (11.00) was observed at 5 °C for 24 h in partial shade.

Plant Height (cm)

The data related to plant height of garlic are presented in Table 3. Analysis of variance revealed that photoperiod had a significant effect ($P < 0.05$), whereas vernalization and the interaction between vernalization and photoperiod were statistically non-significant ($P > 0.05$). Numerically, the tallest plants (33.77 cm) were observed at 7 °C for 48 h, followed by 33.25 cm at 5 °C for 24 h, while the shortest (30.75 cm) occurred at 5 °C for 48 h. On average, differences between 5 °C (32.00 cm) and 7 °C (32.76 cm) treatments were minimal, indicating that vernalization temperature and duration had little measurable influence on plant height. Photoperiod, however, significantly affected plant height, as garlic grown under sunlight (36.38 cm) attained greater height compared with plants under partial shade (27.62 cm). Although the interaction between vernalization and photoperiod was non-significant, numerical trends suggested that the maximum height (39.50 cm) occurred under 7 °C for 24 h in sunlight, whereas the minimum (24.00 cm) was noted under the same treatment in partial shade.

Fresh Biomass of Plant (g)

The data related to fresh biomass of garlic are presented in Table 3. The analysis of variance showed that photoperiod significantly affected fresh biomass ($P < 0.05$), while vernalization and the interaction between the vernalization and photoperiod were non-significant ($P > 0.05$). For vernalization, the highest fresh biomass (8.31 g) was obtained at 7 °C for 48 h, followed by 8.13 g at 5 °C for 24 h. The lowest fresh biomass (7.08 g) was recorded at 5 °C for 48 h. On average, cloves vernalized at 7 °C produced slightly higher biomass (7.95 g) than those treated at 5 °C (7.61 g). Concerning the photoperiod, plants grown under sunlight produced significantly higher fresh biomass (8.84 g) compared to those under partial shade (6.72 g). The interactive effect of vernalization and photoperiod was statistically non-significant. Nevertheless, the highest biomass (9.29 g) was recorded under 7 °C for 24 h in sunlight, whereas the lowest (5.82 g) was observed under 5 °C for 48 h in partial shade.

Leaf Weight (g)

The data related to leaf weight of garlic are presented in Table 4. The analysis of variance showed that photoperiod had a highly significant effect ($P < 0.05$), whereas vernalization and the interaction between vernalization and photoperiod were statistically non-significant ($P > 0.05$). In case of vernalization, the highest mean leaf weight (3.23 g) was recorded at 7 °C for 24 h, closely followed by 3.15 g at 5 °C for 24 h. The lowest mean leaf weight (2.71 g) was observed at 5 °C for 48 h.

Overall, vernalization treatments showed minor differences in leaf weight. Regarding photoperiod, plants grown under sunlight produced significantly higher leaf weight (3.71 g) compared to those under partial shade (2.39 g). The interactive effect of vernalization and photoperiod was statistically non-significant. However, the maximum leaf weight (4.26 g) was observed at 7 °C for 24 h in sunlight, whereas the minimum (2.21 g) was noted at the same temperature under partial shade.

Days to Harvest at Green Stage

The data related to days to harvest at the green stage of garlic are presented in Table 4. The analysis of variance indicated that vernalization, photoperiod, and their interaction significantly influenced the days required to harvest ($P < 0.05$). Regarding vernalization, cloves treated at 7 °C for 48 h required the greatest number of days to harvest (91.50 days), followed by 91.00 days at 5 °C for 24 h. The fewest days to harvest (89.00) were recorded at 7 °C for 24 h. In terms of photoperiod, plants grown under partial shade took longer to reach the green harvest stage (92.75 days) compared to those grown under sunlight (88.00 days). The interactive effect of vernalization and photoperiod revealed that the maximum time to harvest (96.00 days) occurred under 7 °C for 48 h in partial shade, while the minimum (85.00 days) was noted under 7 °C for 24 h in sunlight. The combined influence of extended vernalization and low-light conditions likely delayed physiological development by slowing photosynthetic activity and carbohydrate accumulation, which are essential for bulb and leaf expansion. Reduced light intensity under partial shade may have suppressed metabolic activity and delayed chlorophyll synthesis, leading to slower maturation. In contrast, shorter vernalization under sunlight probably enhanced metabolic recovery after cold exposure, thereby accelerating plant growth and advancing maturity.

DISCUSSION

The current study demonstrated that vernalization and photoperiodic regimes influenced various growth and developmental characteristics of garlic. In general, photoperiod (sunlight vs. partial shade) had a significant positive effect on vegetative traits, including leaf length, leaves per plant, plant height, fresh biomass, and leaf weight, while vernalization mainly affected the timing of sprouting and days to harvest. These findings agree with previous reports indicating that photoperiod and temperature are the principal environmental signals regulating the growth and development of bulbous *Allium* species (Dong *et al.*, 2013; Takagi, 2020).

Photoperiod and temperature serve as the primary regulators of bulbing and related processes. Previous studies have shown that long photoperiods (14–16 h) and higher growing temperatures (≈ 25 – 30 °C) promote bulbing in garlic and other alliaceous crops (Brewster, 2007; Dong *et al.*, 2013; Takagi, 2020). In the present experiment, sunlight exposure resulted in higher mean vegetative growth and biomass accumulation compared to partial shade, consistent with this pattern. These results reaffirm that photoperiodic signaling interacts with thermal cues to coordinate vegetative expansion and bulbing transitions under favorable conditions (Mathew *et al.*, 2010).

Vernalization notably affected plant phenology, particularly the duration from sowing to sprouting and from planting to harvest (Tables 1 and 4). Although some effects on sprouting percentage were not statistically significant, the observed numerical differences suggest that exposure to cold influenced developmental rate. The role of vernalization in promoting reproductive transition and bulb development has been reported in other species as well (Johkan *et al.*,

2012; Mallah *et al.*, 2025). Temperature-driven alterations in carbohydrate and protein metabolism, and changes in secondary compound synthesis, have been proposed as mechanisms by which cold exposure modifies phenological events (Kim *et al.*, 2009; Ha, 2014). The current findings agree with earlier work on ornamentals, where the duration and temperature of cold treatment interacted with photoperiod to modify flowering and organ development (Lopez *et al.*, 2005; Lopez and Runkle, 2008).

Photoperiod also exerted a strong effect on vegetative morphology. Plants grown under sunlight produced longer leaves, heavier leaf mass, taller canopies, and greater biomass than those grown under partial shade, while the number of leaves per plant followed a similar trend. These findings correspond with prior studies showing that light quality, duration, and intensity significantly influence leaf expansion, internode elongation, and biomass accumulation (Fan *et al.*, 2013; Jung *et al.*, 2013; Song *et al.*, 2012). Enhanced vegetative growth under natural sunlight also aligns with observations that light directly affects photosynthetic efficiency and assimilate supply, contributing to higher plant mass (Chia and Kubota, 2010; Yang *et al.*, 2013; Fan *et al.*, 2013).

Varietal specificity and cultivar-dependent responses to environmental manipulations have been documented to affect bulbing behavior and yield performance (Panthee *et al.*, 2006; Dong *et al.*, 2013). Physiological differences such as variations in soluble proteins, sugars, and phenolic sulfur compounds could have contributed to the diverse responses observed, as metabolic capacity to synthesize carbohydrates and secondary metabolites influence both bulb initiation and expansion (Panthee *et al.*, 2006). The green stage of harvest was influenced by both vernalization and photoperiod, where longer vernalization under partial shade tended to delay bulbing and maturity, while shorter vernalization combined with sunlight exposure accelerated these processes. These results agree with earlier findings that photothermal regimes influence developmental rate and organ growth (Lopez *et al.*, 2005; Lopez and Runkle, 2008). Maturity and bulb yield correlations observed by other researchers (Panthee *et al.*, 2006) support the concept that harvest timing and yield potential can be adjusted through managing vernalization duration and day length. Physiologically, these effects may result from integrated changes in hormonal signaling, carbohydrate allocation, and gene expression governing floral and bulb initiation. Temperature alters enzymatic activity and metabolic rates (Kim *et al.*, 2009), whereas light modulates photoreceptor-mediated developmental pathways and assimilate production (Kim *et al.*, 2009; Jung *et al.*, 2013). Artificial lighting may partly substitute for natural day length during low-light seasons, though responses vary with species, genotype, and environmental conditions (Chia and Kubota, 2010; Yang *et al.*, 2013). Morphological characteristics such as stem elongation, branching, and flower initiation are also sensitive to combined temperature and light regimes (Song *et al.*, 2012; Fan *et al.*, 2013; Yang *et al.*, 2013).

While the present results are consistent with known physiological mechanisms, the study was limited to a single garlic variety, grown under pot conditions and within one experimental environment. Therefore, broader multi-environment trials across diverse genotypes are needed to validate these findings. From a practical standpoint, the combination of moderate vernalization (7 °C for 24 h) with full sunlight appears promising for achieving earlier sprouting and vigorous early growth, which can benefit growers aiming for accelerated production cycles under mild winter conditions.

CONCLUSION

The results indicate that garlic cloves vernalized at 7 °C for 24 h exhibited the most vigorous growth, produced the highest biomass, and reached harvest maturity earliest. Photoperiod also played a significant role, with plants grown under sunlight outperforming those in partial shade across all growth parameters, including leaf length, plant height, fresh biomass, and leaf weight. These findings suggest that vernalizing garlic cloves at 7 °C for 24 h followed by cultivation under full sunlight can enhance early growth and allow earlier harvesting at the green stage, offering practical benefits for growers aiming for accelerated and high-quality production. However, since the present study was conducted under controlled pot conditions using a single variety, future research should evaluate multiple cultivars across diverse field environments to validate these results and optimize vernalization protocols for commercial-scale production.

AUTHOR CONTRIBUTIONS

Maira Raqeeb Tunio: Conducted research, data collection and write-up, Tanveer Fatima Miano Conceptualization, designing, supervision, write up and finalizing the manuscript, Muzafaruddin Chachar: Wrote first draft of paper, review & editing, Ghulam Fatima Tunio & Aaqib Mustafa: Write-up and interpretation of data, Ghulam Rasool Tunio & Shahmeer Khan Tunio: Data collection and statistical analysis, Memoona Islam Majeedano & Sana Shazia Jiskani: Collection of data references management, citations and proof read the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- Amasino, R. (2004). Vernalization, competence, and the epigenetic memory of winter. *The plant cell*, 16(10), 2553-2559.
- Atif, M. J., Amin, B., Ghani, M. I., Hayat, S., Ali, M., Zhang, Y., & Cheng, Z. (2019). Influence of different photoperiod and temperature regimes on growth and bulb quality of garlic (*Allium sativum* L.) cultivars. *Agronomy*, 9(12), 879.
- Brewster, J. L. (2008). Onions and other vegetable alliums. *American Journal of Plant Sciences*, 7(3), 234.
- Brewster, J.L. (2007). The physiology of the garlic. *Horticultural Abstract.*, 4(7); 17–23.
- Cai, Z. Q. (2011). Shade delayed flowering and decreased photosynthesis, growth and yield of Sacha Inchi (*Plukenetia volubilis*) plants. *Industrial Crops and Products*, 34(1), 1235-1237.
- Chachar, Z. A., Miano, T. F., Chachar, M., Chachar, S., Majeedano, M. I., Chachar, N. A., & Jiskani, S. S. (2024). Effects of various nutrients on sprouting, growth, and development of garlic (*Allium sativum* L.) at the green stage. *Plant Bulletin*, 3(1), 133–144.
- Chen, Z. Y., Peng, C., Jiao, R., Wong, Y. M., Yang, N., & Huang, Y. (2009). Anti-hypertensive nutraceuticals and functional foods. *Journal of Agricultural and Food Chemistry*, 57(11), 4485-4499.
- Chia, P. L., & Kubota, C. (2010). End-of-day far-red light quality and dose requirements for tomato rootstock hypocotyl elongation. *HortScience*, 45(10), 1501-1506.
- Dong, Y., Cheng, Z., Meng, H., Liu, H., Wu, C., & Khan, A. R. (2013). The effect of cultivar, sowing date and transplant location in field on bolting of Welsh onion (*Allium fistulosum* L.). *BMC Plant Biology*, 13(1), 1-12.
- Etoh, T. A. K. E. O. M. I., & Simon, P. W. (2002). Diversity, fertility and seed production of garlic. In *Allium crop science: Recent advances* (pp. 101-117). Wallingford UK: CABI Publishing.
- Fan, X. X., Xu, Z. G., Liu, X. Y., Tang, C. M., Wang, L. W., & Han, X. L. (2013). Effects of light intensity on the growth and leaf development of young tomato plants grown under a combination of red and blue light. *Scientia Horticulturae*, 153, 50-55.
- Ha, T. M. (2014). A review of plants' flowering physiology: The control of floral induction by juvenility, temperature and photoperiod in annual and ornamental crops. *Asian Journal of Agriculture and Food Sciences*, 2(3).
- Islam, M. R., Khan, M. S. U., Mokarroma, N., Saha, A., Obaidullah, A. J. M., & Nasim, F. A. (2024). Effect of nitrogen in premature sprouting of garlic (*Allium sativum*). *International Journal of Plant & Soil Science*, 36(7), 852-858.
- Johkan, M., Shoji, K., Goto, F., Hahida, S. N., & Yoshihara, T. (2012). Effect of green light wavelength and intensity on photomorphogenesis and photosynthesis in *Lactuca sativa*. *Environmental and Experimental Botany*, 75, 128-133.
- Jung, E. S., Lee, S., Lim, S. H., Ha, S. H., Liu, K. H., & Lee, C. H. (2013). Metabolite profiling of the short-term responses of rice leaves (*Oryza sativa* cv. Ilmi) cultivated under different LED lights and its correlations with antioxidant activities. *Plant Science*, 210, 61-69.
- Kamenetsky, R. (2007). Garlic: botany and horticulture. *Horticultural reviews-westport then new york-*, 33, 123.
- Kamenetsky, R., Shafir, I. L., Zemah, H., Barzilay, A. & Rabinowitch, H. D. (2004). Environmental control of garlic growth and florogenesis. *Journal of the American Society for Horticultural Science*, 129(2), 144-151.
- Khoo, Y. S. K. & Aziz, Z. (2009). Garlic supplementation and serum cholesterol: a meta-analysis. *Journal of Clinical Pharmacy and Therapeutics*, 34(2), 133-145.
- Kim, D. H., Doyle, M. R., Sung, S., & Amasino, R. M. (2009). Vernalization: winter and the timing of flowering in plants. *Annual Review of Cell and Developmental*, 25(1), 277-299.
- King, R. W., Moritz, T., Evans, L. T., Martin, J., Andersen, C. H., Blundell, C. & Chandler, P. M. (2006). Regulation of flowering in the long-day grass *Lolium temulentum* by gibberellins and the Flowering locus t gene. *Plant Physiology*, 141(2), 498-507.
- Kuete, V. (2017). Medicinal spices and vege Fig:s from Africa: therapeutic potential against metabolic, inflammatory, infectious and systemic diseases. Academic Press. 363-377.
- Li, Q., & Kubota, C. (2009). Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. *Environmental and experimental botany*, 67(1), 59-64.
- Lopez, R. G., & Runkle, E. S. (2006). Effect of temperature and pseudobulb maturity on flowering of the orchid *Miltoniopsis augres'trinity'*. In XXVII International Horticultural Congress-IHC2006: International Symposium on Ornamentals, Now! 766 (pp. 273-278).
- Lopez, R. G., Runkle, E. S., & Heins, R. D. (2005). Flowering of the Orchid *Miltoniopsis AugresTrinity'*is Influenced by Photoperiod and Temperature. *Acta Horticulturae*, 683, 175.
- Mallah, S., Miano, T. F., Majeedano, S. U., Majeedano, M. I., & Chachar, M. (2025). Optimizing vernalization and photoperiod for enhanced growth and flowering in pansy (*Viola tricolor* L.). *International Journal of Agriculture Innovation and Cutting-Edge Research*, 3(1), 1–7.
- Mathew, D. Forer, Y.; Rabinowitch, H.D. & Kamenetsky, R (2010). Effect of long photoperiod on the reproductive and bulbing processes in garlic (*Allium sativum* L.) genotypes. *Environmental & Experimental Botany*, 7(1); 166–173.

- Mathew, D., Forer, Y., Rabinowitch, H. D. & Kamenetsky, R. (2011). Effect of long photoperiod on the reproductive and bulbing processes in garlic (*Allium sativum* L.) genotypes. *Environmental and Experimental Botany*, 71(2), 166-173.
- Michael, T. B., Shemesh-Mayer, E., Kimhi, S., Gershberg, C., Forer, I., de Ávila, V. T., & Goldstein, R. K. (2018). Temporal and spatial effect of low pre-planting temperatures on plant architecture and flowering in bolting garlic. *Scientia Horticulturae*, 242, 69-75.
- Michaels, S. D., He, Y., Scortecci, K. C., & Amasino, R. M. (2003). Attenuation of flowering locus C activity as a mechanism for the evolution of summer-annual flowering behavior in Arabidopsis. *Proceedings of the national academy of sciences*, 100(17), 10102-10107.
- Panthee, D.R.; KC, R.B.; Regmi, H.N.; Subedi, P.P.; Bhattarai, S. Dhakal, J. (2006) Diversity analysis of garlic (*Allium sativum* L.) germplasms available in Nepal based on morphological characters. *Genetic Resources and Crop Evolution*. 5(3); 205–212.
- Rajasekar, M., Arumugam, T., & Kumar, S. R. (2013). Influence of weather and growing environment on vegetable growth and yield. *Journal of Horticulture and Forestry*, 5(10), 160-167.
- Ritz, C., Pipper, C., Yndgaard, F., Fredlund, K., & Steinrücken, G. (2010). Modelling flowering of plants using time-to-event methods. *European Journal of Agronomy*, 32(2), 155-161.
- Singh, V. K., & Singh, D. K. (2008). Pharmacological effects of garlic (*Allium sativum* L.). *Annual Review of Biomedical Sciences*, 10, 6-26.
- Song, R., Kelman, D., Johns, K. L., & Wright, A. D. (2012). Correlation between leaf age, shade levels, and characteristic beneficial natural constituents of tea (*Camellia sinensis*) grown in Hawaii. *Food Chemistry*, 133(3), 707-714.
- Statistix. (2006). *Statistics 8.1 user guide, version 1.0*. Analytical software, P.O. Box 12185, Tallahassee fl 32317 USA.
- Takagi, H. (2020). *Garlic (Allium sativum L.)*. In H. D. Rabinowitch & J. L. Brewster (Eds.), *Onions and allied crops: Volume 3. Biochemistry, food science, and minor crops* (pp. 1–57). CRC Press.
- Tattelman, E. (2005). Health effects of garlic. *American family physician*, 72(1), 103-106.
- Wu, C., Wang, M., Dong, Y., Cheng, Z., & Meng, H. (2015). Growth, bolting and yield of garlic (*Allium sativum* L.) in response to clove chilling treatment. *Scientia Horticulturae*, 194(4), 43-52.
- Yang, Z. Q., Li, Y. X., Zhang, J. B., Zhang, J., Zhu, J., Gu, L. L., & Zhang, B. (2013). Effects of the red: far-red light ratio on photosynthetic characteristics of greenhouse cut Chrysanthemum-Short communication. *Horticultural Science*, 40(1), 40-43.