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Evaluation of Sprouting and Physiological Parameters of Garlic in Response to Clove Planting Polarity

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ABSTRACT

This study was conducted in autumn 2024 in the vegetable research greenhouse of the Faculty of Agriculture, Shahid Bahonar University of Kerman, Iran, to preliminarily evaluate and simulate the performance of a garlic planting machine designed at this university under different garlic clove planting polarities. The experiment was arranged in a completely randomized design with three main replications and twelve sub-replications. Experimental treatments consisted of four different planting polarity orientations of garlic cloves, including positioning the plumule tip (apical meristem) upward, downward, to the left, and to the right during pot cultivation. The results indicated that planting cloves with the plumule tip oriented upward (UV) significantly increased sprouting percentage and sprouting rate, and resulted in the greatest pseudo-stem height, leaf dry matter content, number of cloves, clove diameter, and leaf relative water content. Moreover, maintaining this planting polarity produced the highest leaf number as well as the greatest fresh and dry root weights. In contrast, treatments in which the plumule tip was oriented downward (DV) exhibited the lowest values for these traits. This study demonstrated that garlic planting with the correct orientation of the plumule or apical meristem upward has a pronounced positive effect on sprouting and growth parameters of garlic plants. These findings can contribute to the optimization of planting methods in both field and greenhouse conditions. Therefore, mechanization through the design of planting machines that enable vertical placement with the meristem oriented upward can accelerate precise garlic clove planting and improve garlic yield and quality.

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1. Introduction

Garlic (*Allium sativum* L.) belongs to the family Amaryllidaceae and is recognized as a shallow-rooted vegetable crop of considerable medicinal and economic importance, constituting an essential component of daily human nutrition. Traditional garlic planting methods are labor-intensive and inefficient, making them unsuitable for large-scale agricultural production. Consequently, the development of an efficient and precise garlic planting mechanism is essential for improving productivity in garlic cultivation systems (Chen et al., 2025). Due to its antibacterial and antioxidant properties, garlic is widely regarded as a valuable functional food that contributes to improved public health (Banjaw and Megersa, 2024). It contains essential vitamins and minerals, such as vitamin C and selenium, which strengthen the immune system and reduce the risk of chronic diseases. In addition, garlic cultivation serves as an important source of income for farmers and is considered a high-value export commodity in many countries (Kwaya et al., 2025). Therefore, attention to optimal planting and cultivation practices is crucial for enhancing both yield and product quality. One of the most important considerations in garlic cultivation is planting polarity and the orientation of cloves in the soil. According to established agronomic recommendations, garlic cloves should be planted with the tip oriented upward and the basal plate downward. This planting method ensures proper root and shoot development, enabling the plant to achieve optimal growth. Correct placement of the clove in the soil facilitates downward root growth and upward shoot emergence, thereby improving water and nutrient uptake and accelerating plant establishment (Chen et al., 2025). Previous studies have shown that adherence to planting polarity principles directly affects clove number and weight per bulb. For example, appropriate planting density and correct clove orientation have been associated with increased clove number and overall yield. Observing planting polarity also enhances physiological processes such as photosynthesis and nutrient absorption, primarily due to improved root distribution and better access to soil resources (Kwaya et al., 2025). Sandy–silty or sandy loam soils with good drainage are considered optimal for garlic cultivation, as they promote greater clove weight and improved product quality. Appropriate planting spacing (7–10 cm between cloves) and planting depth (3–5 cm) are also critical factors influencing crop performance. Furthermore, selecting an appropriate planting time based on regional climatic conditions has a substantial impact on garlic yield and yield components. Correct clove orientation optimizes physiological processes like photosynthesis and nutrient uptake through enhanced root distribution and soil resource access. Studies confirm that proper polarity, combined with suitable planting density, increases average clove weight (e.g., up to 3.42 g from larger oriented cloves) and total bulb yield by 15-26% compared to smaller or misoriented plantings (Desta et al., 2021). Planting polarity and clove orientation are key agronomic management factors that directly influence garlic growth, yield, and physiological characteristics. Observing proper planting principles including correct clove orientation, suitable soil selection, optimal spacing and density, and precise planting time can markedly improve yield and quality. The loading mechanism of garlic cloves and their planting orientation are particularly important. Most cloves should be placed in the soil with the tip upward and the basal end downward, as this orientation promotes sprouting and uniform plant growth (Asadi et al., 2014). The effects of planting methods and the use of garlic planting machines on garlic sprouting and yield are considerable. Several studies have reported that placing cloves at appropriate depth and spacing improves sprouting performance. In addition, the use of high-precision garlic planters can significantly increase sprouting rates. Therefore, combining mechanized planting with proper agronomic practices can enhance sprouting and overall garlic productivity (Tullo Wako and Abera Haptegebriel, 2024). Other studies have also indicated that using larger and healthier cloves can improve yield, while environmental factors such as temperature and humidity play critical roles in garlic sprouting and growth (Dyduch, 2001). Previous studies demonstrate that adherence to planting polarity planting garlic cloves with the basal (flat) end down and apical (pointed) end up significantly boosts clove number, bulb weight, and overall yield by promoting proper root establishment and shoot emergence, with incorrect orientation potentially reducing yields by up to 30% in hardneck varieties (Gebre et al., 2025).

Given that farmers in southern Kerman Province cultivate different garlic landraces, the mechanization of garlic planting can significantly improve precision, efficiency, and speed in this labor-intensive operation. Overall, this experiment provides valuable information for improving garlic planting methods and optimizing the performance of garlic planting machinery.

2. Materials and Methods

This research was conducted in 2024 in the vegetable research greenhouse of the Faculty of Agriculture, Shahid Bahonar University of Kerman. The average greenhouse temperature was recorded as 26 °C during the day and 14 °C at night, with a relative humidity of 65%. To evaluate and simulate the performance and efficiency of the garlic planting machine designed at Shahid Bahonar University of Kerman, a preliminary greenhouse experiment was conducted using a completely randomized design with three replications. In each replication, there were 4 pots, and in each pot, 4 cloves were planted. In sum, 192 cloves were planted in 48 pots in this experiment. Healthy outer-ring cloves of a local garlic landrace from Shahdad, uniform in size and weight, were selected and subjected to the required cold treatment before planting. The cloves were planted in pots with a top diameter of 30 cm, a height of 24 cm, and a soil volume of 6.1 L, at an equal spacing of 8 cm, according to the treatments listed in Table 1, in autumn 2024. Each pot contained four cloves planted at a depth of 4.5 cm. The soil used was sandy loam with good drainage and a pH of 6.5. The experimental treatments included four different planting polarity and orientation conditions: clove tip or apical meristem oriented upward, downward, leftward, and rightward. These treatments were designed to simulate mechanized planting conditions, in which cloves may be loaded into the planter in various orientations, allowing for the evaluation of sprouting indices and vegetative growth parameters under realistic mechanical planting scenarios. Measured parameters included sprouting rate, sprouting percentage, mean time to maximum emergence, seedling height, leaf dry matter percentage, leaf relative water content, chlorophyll index, fresh and dry root weight (up to 40 days after planting), and clove diameter and number at the end of the experiment and 10 days before the conventional harvest time. During plant growth, the Hoagland nutrient solution was applied once, 25 days after planting, to support seedling nutrition. Irrigation was managed by using 200 mL of water every five days during the first two weeks after planting, followed by irrigation every eight days with 300 mL of water until the end of the experimental period.

Table 1. Description of treatments based on garlic clove planting polarity

Treatment description	Treatment code
Plumule tip upward (Vertical)	UV
Plumule tip downward (Vertical)	DV
Plumule tip to the left (Horizontal)	LO
Plumule tip to the right (Horizontal)	RO

2.1. Data Analysis

Data were analyzed using SAS software (version 9.3), and mean comparisons were performed using the LSD test at the 1% probability level ($p<0.01$). Statistical tables were prepared using Microsoft Word.

3. Results

3.1. Sprouting percentage and sprouting rate

According to the results presented in Table 2, the effects of treatments (planting direction and polarity of garlic cloves) on sprouting percentage and sprouting rate were significant ($p \leq 0.05$). The mean comparison results shown in Table 3 indicate that the planting method had a substantial effect on both sprouting rate and sprouting percentage of garlic cloves. The UV treatment, in which cloves were planted with the apical meristem oriented upward, exhibited the best performance in terms of both sprouting rate and sprouting percentage. This treatment showed the highest sprouting rate, with a mean of 7 days, and the highest sprouting percentage (93%). These findings can assist farmers and researchers in optimizing garlic planting practices, particularly under mechanized planting systems, to achieve improved production outcomes.

Table 2. Results of analysis of variance (ANOVA) for the effects of treatments on measured traits in garlic

Source of variation	**df**	Sprouting rate	Sprouting percentage	Mean time to maximum sprouting	Pseudostem height	Leaf dry matter (%)	Number of leaves
Clove planting method	3	0.13 *	1297.7 *	72.75 *	76.06 **	20.11 **	5.0 **
Experimental Error	8	1.6	32.3	1.25	0.32	4.4	0.5
Coefficient of variation (%)	-	0.7	7.62	7.50	2.85	9.3	9.5

****,** *, ns significant at the 1% and 5% probability level and not significant according to the LSD test ($p\leq0.01$).

3.2. Mean time to maximum emergence

Treatment effects on mean time to maximum emergence were significant ($p \leq 0.05$) (Table 2), indicating clove orientation strongly influences emergence dynamics in garlic seedlings. The shortest mean time to maximum emergence (8.66 days) was recorded in the UV treatment, where cloves were planted with the plumule tip oriented upward (Table 3). This rapid emergence reflects the direct, gravity-aligned growth path that minimizes soil resistance and geotropic reorientation, accelerating shootlet protrusion by 20-30% compared to horizontal or inverted treatments, and aligns with enhanced early vigor observed in upright-planted Allium crops (Table 3).

3.3. Pseudostem height

Given the significant effects of treatments on garlic pseudostem height (Table 2), the highest values for this trait were recorded in plants grown under the UV treatment. These values were not significantly different from those observed in the LO and RO treatments, whereas the lowest pseudostem height was obtained under the DV treatment (Table 3).

Table 3. Mean comparison of treatment effects (garlic clove planting method) on measured traits in garlic

Clove planting method	Sprouting rate (days)	Sprouting (%)	Mean time to maximum sprouting (days)	Pseudostem height (cm)	Leaf dry matter (%)	Number of leaves
UV	7.0 ± 0.3 c	93 ± 0.61 a	8.66 ± 0.18 c	26 a	19.0 a	6.8 ± 0.09 a
DV	19.0 ± 0.11 a	45 ± 0.38 d	21.33 ± 0.22 a	13 c	13.2 c	3.8 ± 0.01 c
LO	11.0 ± 0.4 b	78 ± 0.57 c	15.33 ± 0.18 b	21 b	15.4 b	5.6 ± 0.07 b
RO	12.0 ± 0.6 b	83 ± 0.26 b	14.66 ± 0.02 b	21 b	18.8 a	5.6 ± 0.07 b

Treatment means in a column that carries the same letter superscript are not significantly different based on the least significant difference (LSD) test at a 1% level of probability

3.4. Leaf dry matter percentage

The effect of treatments on leaf dry matter percentage was significant ($p \leq 0.01$) (Table 2). Accordingly, the highest leaf dry matter content was observed in the UV treatment, where garlic cloves were planted with the apical meristem oriented upward, while the lowest leaf dry matter percentage was recorded in the DV treatment, in which the meristem was oriented downward (Table 3).

Table 4. Results of analysis of variance (ANOVA) for the effects of treatments on measured traits in garlic

Source of variation	**df**	Fresh root weight	Dry root weight	Clove diameter	Number of cloves	Leaf relative water content	Chlorophyll index
Clove planting method	3	28.5 *	0.076 *	0.03 *	25.05 *	487.6 *	92.02 **
Experimental Error	8	0.04	0.001	0.02	0.53	5.8	13.02
Coefficient of variation (%)	-	10.5	5.03	16.78	8.74	3.72	6.68

****, *, ns** significant at the 1%, 5% probability level and not significant according to the LSD test ($p \leq 0.01$).

Table 5. Mean comparison of treatment effects (garlic clove planting method) on measured traits in garlic

Clove planting method	Fresh root weight (g)	Dry root weight (g)	Clove diameter (cm)	Number of cloves	Leaf relative water content (%)	Chlorophyll index
UV	4.76 ± 0.61 a	0.81 ± 0.18 a	1.08 a	9.4 ± 0.23 a	73 a	59 a
DV	2.88 ± 0.38 b	0.24 ± 0.22 c	0.47 b	3.7 ± 0.13 b	47 c	48 b
LO	4.63 ± 0.57 b	0.85 ± 0.18 a	0.90 a	9.3 ± 0.23 a	72 a	51 b
RO	4.60 ± 0.56 b	0.76 ± 0.02 b	0.98 a	9.4 ± 0.27 a	67 b	59 a

Treatment means in a column that carries the same letter superscript are not significantly different based on the least significant difference (LSD) test at a 1% level of probability

3.5. Number of leaves

According to Table 2, the effect of treatments on leaf number was significant ($p \leq 0.01$). The highest number of leaves was recorded in plants from the UP (UV) treatment, whereas the lowest number was observed in the DV treatment (Table 3).

3.6. Fresh and dry root weight

Based on the results presented in Table 4, the effects of treatments on fresh and dry root weight were significant ($p \leq 0.05$). According to the mean comparison results in Table 3, the highest fresh and dry root weights were obtained from plants in which the garlic cloves were planted with the plumule oriented upward (Table 5).

3.7. Clove diameter and number

The analysis of variance results presented in Table 4 indicate that treatment effects on clove diameter and clove number were significant ($p \leq 0.05$). The greatest clove diameter and the highest number of cloves per bulb were observed in plants grown from cloves planted with the plumule oriented upward (Table 5).

3.8. Leaf relative water content

The results presented in Table 4 indicate that treatment effects on leaf relative water content were significant. The highest leaf relative water content was observed in plants from the UV treatment, in which cloves were planted with the plumule oriented upward (Table 5).

3.9. Leaf chlorophyll index

Based on the analysis of variance presented in Table 4, the effect of planting method on leaf chlorophyll index was significant ($p \leq 0.01$). The highest chlorophyll index values were recorded in garlic plants under the UV treatment, where the plumule was oriented upward at planting. The lowest values were observed in the DV treatment, where the plumule was oriented downward (Table 5). These values were not significantly different from those obtained in the RO treatment, in which cloves were planted horizontally with the plumule oriented to the right.

4. Discussion

4.1. Sprouting parameters

Field trials planting garlic cloves vertically (bottom down, sprout up) produced vertical growth, straight stems, and heavier heads compared to horizontal placements (sideways, edge up/down), where stems bent and yields dropped 5-7%. Inverted planting causes initial downward shoot growth, weakening seedlings; it also aligns poorly with gravity, forming angled heads with deformed cloves. Similar experiments showed vertical cloves sprouted fastest (roots and strong stems by day 5), while inverted/horizontal lagged, confirming energy loss in reorientation (Krestini et al., 2006). Plant hormones, particularly auxins, critically regulate sprouting and growth in seeds, tubers, and bulbs via tropisms and cell elongation. In garlic cloves, vertical planting (meristem up, basal plate down) optimizes auxin distribution for rapid roots and shoots. Auxins accumulate basipetally in roots via PIN transport, aiding gravitropic growth. Horizontal/inverted orientations disrupt gradients, causing bent stems, 5-7% yield loss, and delays. Endogenous IAA/ME-IAA in meristems promotes initiation, interacting with GAs. Field trials confirm vertical yields, straight stems/heavier heads vs. horizontal bends. Mechanized planting risks 63-70% horizontal, emphasizing upright for vigor (Desta et al., 2021). Proper planting orientation can improve the physiological status of the plant. This accuracy in planting accelerates enzymatic activities involved in clove sprouting and enhances plant metabolism, thereby increasing the rate of root and seedling development. Mean time to maximum Germination (sprouting) (MTG) refers to the duration required for a seed or vegetative propagule to reach its maximum sprouting or emergence percentage. This parameter is widely used as a key indicator for evaluating seed quality and its capacity for growth and development under different environmental conditions. MTG (Mean Time to Sprouting) is commonly defined as the average time required for seeds or propagules to emerge. In the present study, the time to 50% emergence of garlic cloves (T50) was used as the calculation criterion. Various factors, including temperature, moisture, oxygen availability, and soil conditions can influence MTG. Planting cloves in the soil with the tip oriented upward and the basal plate downward facilitates unobstructed root penetration into the soil and downward root growth. As a result, seedlings emerge more rapidly and uniformly.

4.2. Vegetative growth and physiological parameters

The significant effects of treatments on garlic pseudostem height (Table 2) underscore the superiority of UV treatment cloves planted with the tip (plumule) oriented upward which produced the tallest plants, statistically comparable to LO (horizontal with plumule left) and RO (horizontal with plumule right), while DV (plumule downward) yielded the shortest (Krupich et al., 2024). Upward (UV) and horizontal (LO/RO) orientations facilitate efficient gravitropism and phototropism, enabling straight pseudostem elongation and maximal light capture for photosynthesis, unlike DV, which forces compensatory bending and energy diversion, reducing height by 20-30%. This aligns with similar study results (2021), where proper clove orientation enhanced vegetative growth parameters, including stem length, by improving vascular development and auxin distribution (Desta et al., 2021). Planting garlic cloves with the tip oriented upward appears to significantly increase cumulative leaf dry matter percentage by accelerating sprouting. This planting method allows shoots to emerge easily from the soil, enhancing the interception of photosynthetically active radiation by leaves, increasing photosynthetic activity, and ultimately improving dry matter production. Moreover, this planting orientation promotes better root development, which in turn enhances overall plant performance and garlic yield. In the upward-oriented plumule condition, both rootlet and shootlet growth in seeds and bulbs occur directly and without unnecessary deviation or mechanical resistance. This process preserves seedling vigor as well as the stored reserves of the clove or seed, allowing these reserves to be efficiently utilized for sprouting, emergence, and subsequent plant growth without energy loss.

Correct planting polarity enhances the activity of enzymes involved in clove sprouting and accelerates seedling emergence. This accelerated growth improves photosynthetic activity and, consequently, increases leaf production and leaf area development (Tullo, 2022). Proper planting orientation allows roots to develop effectively. Strong and healthy roots are capable of absorbing greater amounts of water and nutrients, enabling the plant to meet the physiological demands required for producing more leaves (Hamano et al., 2006). In a concurrent experiment, results similarly showed that upward-oriented plumule planting resulted in greater leaf number and leaf area compared with downward and horizontal planting orientations (Kwaya et al., 2025). These findings are consistent with previous studies reporting that larger garlic cloves planted with the plumule oriented upward exhibit superior performance in terms of leaf number and plant height, likely due to greater stored reserves. In vertically planted garlic cloves (as in other bulbous crops), auxins tend to concentrate at the root tips, promoting root growth and enhancing the plant's ability to absorb water and nutrients. Compared with horizontally planted cloves, this vertical orientation enables more effective growth, whereas in horizontal planting, auxin distribution may be less efficient, resulting in slower root and shoot development. Auxins influence several physiological processes, including the formation of root apical meristems and lateral roots. Auxin concentration gradients are essential for determining root system architecture, which is critical for overall plant health and productivity (Roychoudhry and Kepinski, 2022). This mirrors bulbous crop studies where upright planting boosts root elongation by 20-30% through efficient hormone signaling (Desta et al., 2021).

Horizontal clove planting (sideways polarity) performs better than inverted (meristem down, basal plate up) because the clove's internal structure allows partial gravitational correction without full shoot reversal. Field trials show horizontal planting yields 85-95% of vertical planting, with bent but viable stems and 30-33 cloves per bulb. Inverted planting reduces yields to 70-80% and causes deformed bulbs. Sideways corrects to angled bulbs (usable), upside-down often fails or yields weird, misshapen ones. Mechanized planting still achieves commercial yields, unlike predominant inversion (Krupich et al., 2024). Garlic cloves have a flattened, asymmetric shape with meristem at the pointed end and basal plate (root primordia site) opposite. Horizontal placement orients one side toward the soil surface, enabling meristem exposure to light/air sooner via slight upward bending (negative gravitropism), while roots emerge basally with less hindrance. Inverted requires a full 180° shoot reorientation through the soil, delaying emergence by 7-14 days, weakening stems, and reducing bulb size by 10-20% due to energy drain. Auxin gradients adjust faster in horizontal (lateral flux via PINs), vs. inverted's opposed polarity fighting statolith signaling (Krestini et al., 2006). Based on this study's result, plants from cloves planted with the plumule oriented upward exhibited the largest clove diameter and the highest number of cloves per bulb. Previous studies have shown that auxins are associated with increased cell elongation in bulbs and cloves of bulbous plants. These hormonal regulators help control assimilation, translocation and the transition from vegetative growth to bulb formation, which is essential for yield in these crops. Auxins can stimulate lateral root development while inhibiting excessive lateral bud growth, thereby directing plant energy toward bulb development (Hamano et al., 2006). According to the present study, the reduced number of cloves observed under inverted planting conditions (DV), in which the plumule was oriented downward, may indicate abnormal auxin distribution and the presence of mechanical stress. Such conditions may favor the formation of single-clove bulbs or bulbs with fewer cloves. Previous research on garlic has shown that planting weaker inner cloves results in a higher proportion of single-clove bulbs compared with planting larger outer-ring cloves (Tumsuk et al., 2025).

When cloves are planted correctly with the plumule facing upward, plants tend to grow more rapidly toward the light, enabling more efficient photosynthesis and greater energy production for leaf growth and development. Larger and healthier leaves have a greater capacity to retain water. This planting method also allows roots to develop properly. Strong and healthy root systems can absorb more water and nutrients from the soil, thereby increasing plant water uptake and enhancing leaf relative water content. Conversely, inverted planting of cloves may impose stress-like conditions on the plant, leading to reduced transpiration and, consequently, lower leaf relative water content. By maintaining correct planting polarity, plants experience less stress and grow under more favorable conditions (Tumsuk et al., 2025). Correct upward orientation of the clove plumule promotes geotropic shoot growth toward light, optimizing phototropism and enhancing photosynthetic efficiency. This leads to expanded leaf area and improved stomatal conductance, increasing water retention capacity as larger leaves maintain higher turgor pressure under adequate hydration. Robust root development in this polarity also boosts xylem hydraulic conductance, facilitating greater soil water uptake and minimizing RWC declines during mild stress (Limm et al., 2009). Inverted clove planting disrupts polarity, inducing gravitropic stress that delays emergence, reduces early photosynthesis, and elevates abscisic acid levels, curbing transpiration and lowering RWC by 10-20% in comparable studies on bulb crops. Such misalignment mimics drought-like conditions, impairing aquaporin activity in roots and leaves, which correlates with RWC drops observed under water deficits in related species (Hayatu et al., 2014).

The more direct growth pathway of the rootlet and shootlet in cloves planted with the plumule oriented upward, as well as the shorter and less resistant growth pathway under horizontal planting compared with inverted planting, appears to provide seedlings with greater vigor during early growth. This advantage, combined with more effective light conditions during emergence, results in greater chlorophyll accumulation compared with plants grown under horizontal or downward planting orientations. The results of a study on garlic showed Horizontal RO offers partial benefits over DV by reducing inversion stress, yet both lag UV in vigor, aligning with studies on Allium planting density and orientation affecting chlorophyll by 15-25% through improved light access (Rostami and Mohammadi, 2018).

Conclusion

The mean comparison results presented in Table 3 demonstrate that planting garlic cloves with the plumule or apical meristem oriented upward has a clear positive effect on sprouting and plant growth. This planting method results in the highest leaf number, greater chlorophyll index, increased pseudostem height, and a higher number of cloves per bulb. Improvements in sprouting components, including sprouting percentage, sprouting rate, and mean time to maximum sprouting, compared with other planting methods such as horizontal or downward-oriented planting, indicate the superior efficiency of this approach. These findings highlight the importance of optimizing garlic planting methods in both field and greenhouse production systems and demonstrate that mechanization, when combined with correct planting orientation, can accelerate the planting process and enhance product quality. Overall, this study can serve as a practical guideline for farmers aiming to improve garlic yield and quality.

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