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Influence of transplanting dates on growth dynamics and harvest period of winter greenhouse cauliflower (*Brassica oleracea* var. *botrytis*) in Trans-Himalayan Ladakh, India

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Abstract

The study investigated the impact of various transplanting dates on growth, yield, and harvest period of cauliflower (*Brassica oleracea* var. *botrytis*) during the winter months within a passive solar Ladakh greenhouse in trans-Himalayan Ladakh region during 2023-24 at DRDO- Defence Institute of High Altitude Research, Leh, Ladakh. Two commercial cauliflower varieties, WS-909 and Amazing, were used with five distinct transplanting dates starting from 4 September 2023, to 14 October 2023 (2023-2024). Despite the extreme temperature fluctuations observed within the greenhouse, curd formation occurred in both varieties across all transplanting dates. The highest gross (1.15 and 0.98 kg), marketable (0.67 and 0.56 kg), and net (0.44 and 0.36 kg) curd weights for WS-909 and Amazing were recorded when transplanting took place on 4 September, 2023. A delay in planting date resulted in a corresponding decrease in gross, marketable, and net curd weights in both varieties. Additionally, increased temperatures in greenhouse contributed to a fuzziness range of 7.6% to 37.5% in harvested curds, which varied according to transplanting date and variety. The delays in transplanting were associated with reduced harvesting durations, decrease in total number of harvests, and, consequently, a decline in overall yield. It is thus suggested that cauliflower be transplanted early during first fortnight of September for optimal yield in this region. Nevertheless, late transplanting ensured availability of fresh cauliflower during peak winter months, and can be traded off with the reduced yield.

Key words: Cold arid region, Curd weight, Gross yield, High altitude, Ladakh greenhouse, Protected cultivation, Transplanting

Cultivating cauliflower (*Brassica oleracea* var. *botrytis*) in the trans-Himalayan Ladakh region demands innovative approaches to ensure food security and enhance income generation for local populace. Greenhouse cultivation, especially during winter, has become a promising solution to surmount these limitations (Angmo *et al*., 2020; Singh *et al*., 2024). Cauliflower is a cool-season crop that prefers moderate temperatures and uniform moisture regimes. It is cultivated for its immature inflorescence and is known as curd. Still, it happens to be a typical summer crop in Ladakh region, where transplanting is done in early-May and reaches maturity in July-September (Stobdan *et al*., 2018), and several environmental factors affect it at various growth stages (Hadley and Pearson, 1998). Thus, cauliflower cultivation is possible only through protected cultivation practices. Winter greenhouses, such as improvised passive solar greenhouses (Angmo *et al*., 2020; Krishna *et al*., 2025), designed to trap heat and maintain optimum growing conditions during cold season, enable farmers to grow cauliflower even when the outdoor temperature drops below freezing.

Transplanting time is an important factor affecting the growth and development of cauliflower. It influences the exposure of crop to environmental factors critical for growth, such as temperature, light intensity, and photoperiod; these, in turn, affect important physiological events, including germination, vegetative growth, curd formation, and maturation (Hafez *et al*., 2023; Chiranjiv *et al*., 2025). The optimal temperatures at different growth periods are very necessary for cauliflower. Excessively low temperatures or unseasonal warmth can lead to stunted growth, delay curd initiation, or produce low yields (Mulodia *et al*., 2022). Therefore, transplanting dates in high-altitude areas like Ladakh, with large variations in day lengths and large diurnal temperature fluctuations, must be appropriately synchronized with the existing conditions for optimal crop performance. Early transplanting exposes tender seedlings to low temperatures, which may delay growth and increase the chances of frost damage to the crop (Pradhan *et al*., 2023). Thus, study was carried out to evaluate the influence of different transplanting dates on growth dynamics, phenological development, harvest period, and yield of cauliflower in winter greenhouses.

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MATERIALS AND METHODS

The experiment was conducted in a Ladakh passive solar greenhouse (Ladakh Greenhouse) at the Defence Institute of High Altitude Research in trans-Himalayan high-altitude region of Ladakh, India (altitude 3340 m from MSL, 34°08.2'N; 77°34.3'E) during 2023-24 winter season. The greenhouse is a medium-sized improvised passive solar greenhouse, measuring 90 feet in length, 27 feet in width, and 9 feet in height, oriented in an east-west direction. The structure features cement-plastered stone walls on three sides, with the east and west walls being 1.5 feet thick, while the north wall is 2 feet thick. The south-facing side is covered with a clear, UV-stabilized 16-mm triple-layer polycarbonate panel. A portion of the east and west walls is clad with a distinct material up to 4 feet. The greenhouse has a sloped wooden roof insulated on the northern side with a layer of straw and soil. Temperature regulation is achieved through manually operated ventilators located on the south-facing and west frames of the greenhouse. Notably, no supplementary lighting or heating systems were utilized, and the structure was not outfitted with a thermal blanket, even during the peak winter months. The temperature was recorded daily with a Hygro-Thermometer Clock (Extech Instruments, USA) (Table 1).

A randomized block design was implemented, with three replications per treatment. Each replication comprised plots measuring 2.1 m × 1.5 m, containing 20 seedlings arranged with a spacing of 35 cm × 35 cm. Farmyard manure (FYM) and vermicompost were applied during field preparation at 3.8 kg m^{-2} and 317 g m^{-2}, respectively. Throughout the growing season, no herbicides or pesticides were utilized. Irrigation was provided through flooding during the initial establishment phase and throughout subsequent growth stages at a weekly interval. Seedlings grown in a passive solar greenhouse were transplanted manually on five distinct dates: 4 September 2023, 14 September 2023, 24 September 2023, 4 October 2023, and 14 October 2023. Manual weeding was performed twice during the growing season to ensure optimal growth conditions.

Plant height, leaf count, and stem diameter were recorded 30-60 and 60-90 days after transplanting (DAT). Leaf chlorophyll index was assessed using the SPAD measurement method (Chlorophyll Meter SPAD-502Plus, Konica Minolta, Japan) on fully expanded upper leaves. Curd weight at fresh market maturity was measured three times throughout the season. All curds were trimmed to meet market standards before weighing. At harvest, plants were evaluated for curd quality defects, and curds exhibiting symptoms of physiological disorders were documented. Additionally, number of days taken for curd initiation, first harvest, peak harvest, and last harvest were calculated based on transplanting dates (DAT) for each planting date.

All experiments were conducted in triplicate to ensure reliability. The results of the experiments were presented as mean values ± standard deviation (SD). Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, SPSS Corporation, Chicago, Illinois, USA). A one-way analysis of variance (ANOVA) was executed, followed by post-hoc analysis employing a two-sided Tukey's Honestly Significant Difference (HSD) test, with a significance level set at $p \leq 0.05$.

RESULTS AND DISCUSSION

The data on plant height exhibited non-significant variation for WS-909 at 60 and 90 days after transplanting (DAT) (Table 2). In contrast, the Amazing variety displayed significant variation in plant height during the 60 DAT. The maximum plant height (49.4 cm) for the Amazing at 60 DAT was observed on 4 October 2023 DOT (date of transplanting), while minimum height (41.7 cm) was recorded on 14 September 2023 DOT. The variations in plant height across transplanting dates highlight the role of genetic and environmental factors in winter-grown greenhouse cauliflower growth. Over 90 DAT period, range of heights in Amazing variety narrowed, suggesting that while transplanting date influences early vegetative growth, genetic factors become more significant as plants mature and form curds. These findings align with Sultana *et al.* (2019).

The number of leaves/plant also did not vary significantly for variety WS-909; however, highest

Table 1: Temperature during cauliflower growing season in winter

Month	Temperature in open field (˚C)		Temperature inside Ladakh Greenhouse (˚C)		Difference in open field and greenhouse temperature (˚C)	
	Max.	Min.	Max.	Min.	Max.	Min.
September (2023)	23.1±3.3	9.3±3.3	49.3±4.4	15.5±2.0	25.2±2.5	5.8±1.0
October (2023)	13.3±3.1	-0.4±3.0	37.8±4.9	12.1±2.5	24.7±6.4	14.3±0.6
November (2023)	9.7±2.3	-5.0±3.1	37.3±2.4	6.5±1.0	28.4±2.6	13.2±0.7
December (2023)	4.6±1.4	-11.3±2.4	26.9±2.3	3.9±1.1	22.5±2.9	15.2±1.8
January (2024)	3.6±1.5	-12.2±2.0	23.5±2.3	1.5±1.2	20.4±2.9	13.0±2.5
February (2024)	0.5±3.0	-11.0±3.9	34.6±3.7	5.8±2.2	32.6±2.9	15.5±1.9
Mean	**9.1±8.2**	**-5.1±8.4**	**34.9±9.1**	**7.5±5.2**	**25.6±4.3**	**12.8±3.5**

Values represent mean±standard deviation (SD).

number of leaves was observed for 14 September 2023 DOT (20.1) at 90 DAT while lowest number of leaves was noted for 4 October 2023 DOT (18.0). For Amazing, at 60 and 90 DAT, highest number of leaves was noted for 4 September 2023 DOT (17.5; 21.3), whereas lowest number of leaves was recorded for 14 September 2023 (13.3). Similarly, Devi *et al.* (2022) reported that transplanting on November 23 resulted in a higher number of leaves/plant, attributing this to optimal environmental conditions that promote leaf development. Rahman *et al.* (2016) found that planting dates influenced leaf number, with specific dates providing conditions that enhance vegetative growth. These studies underscore the importance of selecting appropriate transplanting dates to optimize leaf development, which is crucial for photosynthetic capacity and overall plant vigour.

The analysis of stem diameter revealed non-significant variation in all transplanting dates for WSS-909 at 60 and 90 days after transplanting (DAT). This uniformity suggests that WS-909 maintains stable stem development regardless of transplanting time, indicating a potential resilience to varying environmental conditions within greenhouse setting. Notably, for Amazon variety, at 60 DAT, the largest stem diameter was observed on 4 September 2023 DOT, measuring 12.5 mm, whereas the smallest was recorded on 14 September 2023, at 9.1 mm. This pattern suggests that while early vegetative growth in Amazing variety may be influenced by transplanting date, stem development stabilizes as the plants mature.

However, a study by Hafez *et al.* (2023) reported that earlier transplanting dates increased stem diameter, attributing this to more favorable environmental conditions during the initial growth stages. Moreover, chlorophyll index values for both varieties, assessed across various transplanting dates, did not exhibit significant differences, ranging from 46.7±1.9 to 51.0 ± 1.9 at 60 and 90 days after transplanting (DAT). This consistency suggests that chlorophyll content in both varieties is relatively unaffected by the transplanting date, indicating a stable photosynthetic performance under greenhouse conditions. Similar observations were made by Akshatha *et al.* (2019), who found that different transplanting dates did not significantly impact chlorophyll content in broccoli, a close relative of cauliflower.

In our study, normal curds were successfully formed even though day temperatures exceeded 25 °C on most days (Fig. 1). This phenomenon may be attributed to the cumulative effects of lower temperatures on the plants, resulting in curd formation once the chilling requirement has been adequately fulfilled (Fujime and Hirose, 1980). No statistically significant variations in curd diameter (14.8 to 18.0 cm) were noted for Amazing and WS-909 varieties. This uniformity suggests that curd size in both varieties is relatively stable and less sensitive to timing of transplanting under the given conditions. In contrast, gross curd weight demonstrated an apparent decline with delayed transplanting.

Marketable and net curd weights followed this trend, with both varieties achieving peak weights on the earliest transplanting date and diminishing with subsequent delays (Table 3). The highest gross curd weight (1.15 kg; 0.98 kg), marketable curd weights (0.67 kg and 0.56 kg), and net curd weights (0.44 kg and 0.36 kg) of both varieties were recorded for 4 September 2023 DOT (date of transplanting), whereas lowest gross curd weight (0.79 kg) and marketable curd weight (0.44) in WS-909 were recorded for 14 October 2023 DOT. As the planting date was delayed, gross, marketable, and net curd weights for both varieties decreased correspondingly. A similar trend was observed for total marketable yield of both varieties. The total marketable

Table 2: Growth parameters of both varieties harvested in winter season (2023-2024)

Parameters	DAT*	WS-909					Amazing				
		Date of transplanting (DOT)					Date of transplanting (DOT)				
		4 Sep 23	14 Sep 23	24 Sep 23	4 Oct 23	14 Oct 23	4 Sep 23	14 Sep 23	24 Sep 23	4 Oct 23	14 Oct 23
Plant height (cm)	60	48.3±4.3^{a}	48.5±3.6^{a}	49.5±6.2^{a}	48.6±6.5^{a}	47.0±3.1^{a}	48.3±2.1^{ab}	41.7±1.3^{b}	47.0±5.6^{ab}	49.4±6.0^{a}	46.6±3.7^{ab}
	90	61.6±5.3^{a}	63.0±3.0^{a}	61.6±2.0^{a}	61.3±5.5^{a}	58.6±2.3^{a}	63.1±4.7^{a}	58.8±6.3^{a}	58.3±3.3^{a}	59.8±7.0^{a}	57.1±3.3^{a}
No. of leaves	60	16.1±2.1^{a}	15.1±1.6^{a}	15.1±1.3^{a}	14.6±0.8^{a}	14.8±0.9^{a}	17.5±2.0^{a}	13.3±0.8^{b}	15.5±1.2^{ab}	13.6±1.0^{b}	14.3±1.0^{b}
	90	19.6±1.0^{ab}	20.1±0.9^{a}	19.8±0.9^{ab}	18.0±1.2^{b}	19.1±1.4^{ab}	21.3±1.7^{a}	21.1±0.9^{a}	20.6±1.3^{a}	16.5±1.5^{b}	17.6±1.2^{b}
Stem diameter (mm)	60	12.5±1.6^{a}	12.4±1.6^{a}	13.1±0.4^{a}	12.3±1.4^{a}	11.9±1.1^{a}	12.5±1.1^{a}	9.1±0.3^{b}	11.6±2.2^{ab}	10.9±1.9^{ab}	10.6±1.2^{ab}
	90	16.4±1.7^{a}	18.0±1.5^{a}	17.0±1.0^{a}	15.7±1.6^{a}	15.9±1.4^{a}	16.6±1.6^{a}	14.3±1.1^{a}	14.3±1.2^{a}	14.3±2.6^{a}	14.9±1.3^{a}
Leaf chlorophyll (SPAD)	60	49.2±4.6^{a}	48.5±1.7^{a}	48.7±2.4^{a}	47.5±2.8^{a}	47.7±2.1^{a}	46.7±1.9^{a}	47.7±3.2^{a}	47.0±2.1^{a}	48.9±4.9^{a}	47.3±2.3^{a}
	90	49.5±3.4^{a}	48.9±2.2^{a}	49.6±2.7^{a}	49.0±2.9^{a}	51.0±1.9^{a}	48.1±2.3^{a}	50.0±2.0^{a}	47.6±1.9^{a}	49.2±3.1^{a}	49.3±1.6^{a}

Values represent mean±standard deviation (SD). Means followed by different lowercase letters within a row for each variety indicate significant differences (Tukey's HSD test, $p < 0.05$). *DAT- Days after transplanting

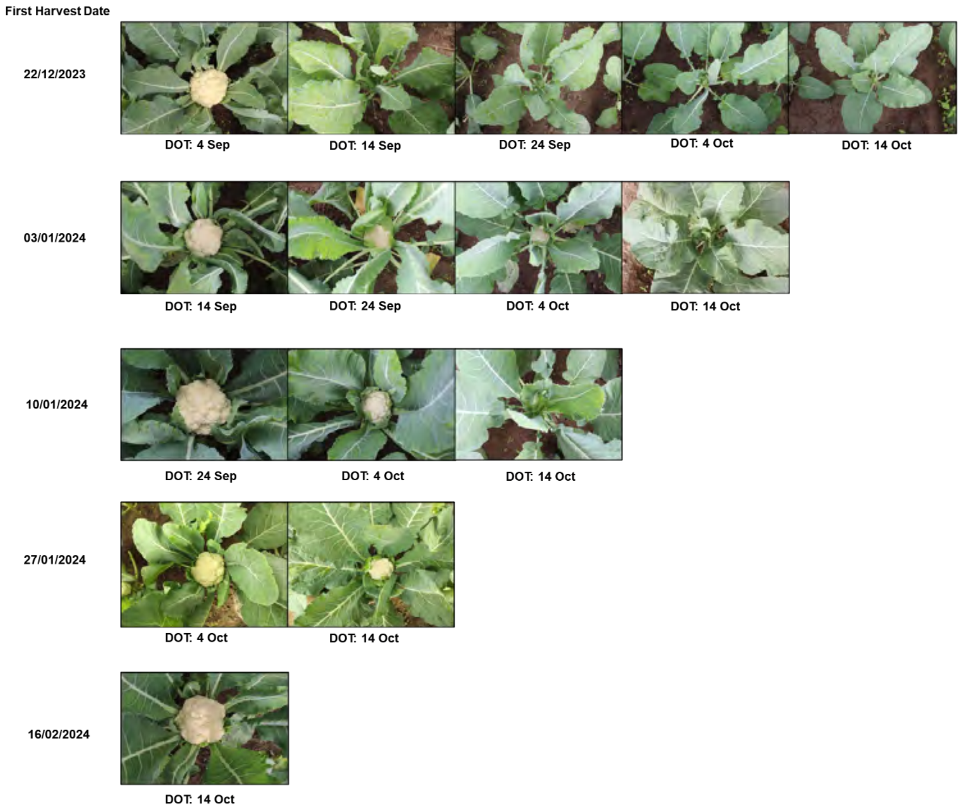

Fig. 1 Comparison between different transplanting dates at the time of first harvest of sequential dates of transplanting (DOT) for cauliflower seedlings

yield ranged from 2.1 to 3.5 kg m^{-2} and 1.6 to 2.1 kg/6.3 m^2 for WS-909 and Amazing, respectively.

Yield of both varieties declined with later transplanting dates, indicating that earlier planting confers a significant advantage in terms of total harvestable produce. Sultana *et al.* (2019) reported that planting cauliflower in November resulted in superior growth and yield, leading to highest economic and biological yields. Similarly, Devi *et al.* (2022) observed that cauliflower transplanted on 23 November achieved significantly higher yields than other dates, highlighting the importance of transplanting timing in maximizing productivity. The decrease in yield with delayed transplanting may be attributed to suboptimal environmental conditions encountered by plants during critical growth phases. Late transplanting can expose cauliflower to unfavorable temperature regimes and reduced light availability, adversely affecting photosynthetic efficiency and curd development. These environmental stresses contribute to reduced gross, marketable, and net curd weights observed in later transplanting dates.

However, marketable curd weight was significantly low compared to the yield potential of both varieties. The yield potential of WS-909 is 1.25-1.50 kg, and that of Amazing is 1-1.5 kg. Low curd weight may be due to higher temperatures inside greenhouse. High temperatures, specifically those exceeding 22.5-25 °C, are known to impact the diameter and weight of cauliflower curd negatively (Nowbuth, 1998; Gopalakrishnan, 2007). Additionally, Wheeler *et al.* (1995) documented reduced total biomass at the final harvest due to elevated temperatures. It has been observed that there is a decrease in dry weight of approximately 6% for every 1 °C increase in temperature. Delays in harvesting can lead to the formation of loose or yellow curds as a consequence of high temperatures. Gopalakrishnan (2007) indicated that curds developed in conditions exceeding 25 °C tend to appear small, loose, or yellow.

Physiological disorder

Several physiological disorders affect the market quality and yield of cauliflower curds. Fuzziness, characterized by a velvety or hairy appearance of curd, was noted in both varieties, with incidence rates ranging from 7.6 % to 13.6 % in WS-909 and from 15.5 % to 37.5% in Amazing, depending on the transplanting date (Table 3). Curd defects are associated with temperature fluctuations that fall outside the optimal range for a specific stage of development. Normal curds typically form within a temperature range of 10-25 °C, depending on variety. Fuzziness is observed when temperatures exceed this range, and its severity increases with rising temperatures (Fujime and Okuda, 1996). Also, fuzziness was more frequent with early transplanting dates, particularly in Amazing variety. Further, throughout the growing season, mean maximum temperature recorded in greenhouse was 34.9 °C, significantly above the ideal temperature range for curd development. Nevertheless, incidence of fuzziness observed among curds was relatively low. This phenomenon may be attributed to the severity of fuzziness, which tends to diminish when curds are subjected to elevated temperatures during later stages of development (Fujime and Okuda, 1996).

Harvest period

Different transplanting dates significantly impacted various attributes related to the harvest period (Table 4). The timing of curd initiation in cauliflower is a critical factor influencing yield and quality. The duration for curd initiation varied between 66.3 days and 81.3 days for WS-909 and Amazing varieties. Notably, seedlings transplanted on 4 September 2023 exhibited the longest duration for curd initiation in WS-909 variety, taking a total of 76 days, while minimum duration was recorded at 66.3 days for seedlings transplanted on 14 October 2023. Conversely, in Amazing variety, maximum days for curd initiation were noted for seedlings transplanted on 14 September 2023, which took 81.3 days, whereas minimum was recorded at 71.6±1.5 days for those transplanted on 4 September 2023. Wurr *et al.* (1990) demonstrated that the time from transplanting to maturity and from curd initiation to maturity in cauliflower is quadratically related to the transplanting date, with variations influenced by annual climatic differences.

The study found that later transplanting dates could either shorten or lengthen time to maturity, depending on year, due to temperature-mediated effects on vernalization and curd growth durations. Moreover, a study by Lin *et al.* (2019) found that tropical cauliflower cultivars exhibited different apex development rates under varying temperature treatments, with certain temperatures accelerating curd initiation. These findings underscore the importance of selecting appropriate transplanting dates to synchronize cauliflower development with favorable environmental conditions, thereby optimizing curd initiation timing.

The timing of transplanting significantly influenced the harvest dynamics of cauliflower varieties, as evidenced by the data on both varieties (Table 4). The seedlings transplanted on 14 October 2023 required longest period for first harvest in both varieties, which totaled 124 days. The peak harvest days for both varieties ranged from 114.6 days to 133.6 days, with peak harvest periods for all transplanting dates aligning closely. The interval for final harvest from transplanting date extended from 129.3 days to 151.6 days for all transplanting dates in both varieties. The total harvest duration from initial to final harvest varied between 5.3 days and 43.3 days for both varieties. The extended time to first harvest observed in the 14 October transplanting may be attributed to suboptimal environmental conditions encountered during critical growth phases. Later transplanting dates can expose cauliflower plants to cooler temperatures and reduced daylight, potentially delaying developmental processes such as curd initiation and maturation. Wurr *et al.* (1990) reported that time from transplanting to maturity in cauliflower is influenced by transplanting date, with later dates potentially leading to longer durations to maturity due to temperature-mediated effects on vernalization and curd growth. The variability in total harvest duration suggests that earlier transplanting dates may contribute to a more concentrated and potentially more manageable harvest period. This compression of harvest window can be advantageous for growers aiming to optimize labor and market timing. Conversely, later transplanting dates may result in a prolonged harvest period, which could complicate harvest logistics but also provide an extended supply of fresh produce to the market.

Table 3. Yield attributes of both varieties in winter season (2023-2024)

Variety	Date of transplanting	Curd diameter (cm)	Gross curd weight (kg)	Marketable curd weight (kg)	Net curd weight (kg)	Total marketable yield (kg)/m²	Fuzziness (%)
	4 Sep 2023	18.0±0.8ᵃ	1.15±0.0ᵃ	0.67±0.1ᵇ	0.44±0.0ᵃ	3.5±0.2ᵃ	12.0±0.4ᵇᶜ
	14 Sep 2023	17.0±1.3ᵃ	1.12±0.0ᵇ	0.57±0.0ᵃᵇ	0.38±0.0ᵃ	3.3±0.2ᵃ	7.6±0.4ᵈ
WS909	24 Sep 2023	17.1±1.1ᵃ	0.99±0.1ᵃᵇ	0.55±0.0ᵃᵇ	0.44±0.0ᵃ	2.9±0.3ᵇ	13.0±0.2ᵃᵇ
	4 Oct 2023	17.0±0.5ᵃ	0.86±0.0ᵇ	0.47±0.0ᵃᵇ	0.36±0.0ᵃ	2.2±0.1ᶜ	10.8±0.7ᶜ
	14 Oct 2023	16.6±0.2ᵃ	0.79±0.0ᵇ	0.44±0.0ᵇ	0.34±0.0ᵃ	2.1±0.2ᶜ	13.6±0.6ᵃ
	4 Sep 2023	15.5±0.5ᵃ	0.98±0.1ᵃ	0.56±0.0ᵃ	0.36±0.0ᵃ	2.0±0.2ᵃ	37.5±0.6ᵃ
	14 Sep 2023	15.0±0.8ᵃ	0.76±0.1ᵃ	0.44±0.1ᵃ	0.31±0.0ᵃ	1.6±0.2ᵇ	15.5±0.4ᶜ
Amazing	24 Sep 2023	15.3±0.5ᵃ	0.81±0.0ᵃ	0.48±0.0a	0.32±0.0ᵃ	2.0±0.1ᵃ	21.0±0.3ᵇ
	4 Oct 2023	14.8±1.0ᵃ	0.77±0.1ᵃ	0.45±0.0ᵃ	0.31±0.0ᵃ	2.1±0.2ᵃ	21.6±0.4ᵇ
	14 Oct 2023	14.8±1.0ᵃ	0.78±0.0ᵃ	0.46±0.0ᵃ	0.32±0.0ᵃ	1.9±0.3ᵃ	22.2±1.3ᵇ

Values represent mean±standard deviation (SD). Means followed by different lowercase letters within a row for each variety indicate significant differences (Tukey's HSD test, $p < 0.05$).

Table 4. Harvest period attributes of two commercial cauliflower varieties obtained in winter season (2023-2024)

Variety	**WS909**					**Amazing**				
Date of transplanting	**4 Sep 23**	**14 Sep 23**	**24 Sep 23**	**4 Oct 23**	**14 Oct 23**	**4 Sep 23**	**14 Sep 23**	**24 Sep 23**	**4 Oct 23**	**14 Oct 23**
Days for curd initiation (DAT)	76.0 ± 1.0^{a}	72.6 ± 1.5^{ab}	75.6 ± 1.5^{ab}	71.3 ± 2.5^{b}	66.3 ± 1.5^{c}	71.6 ± 1.5^{c}	81.3 ± 1.5^{a}	72.3 ± 2.0^{c}	76.3 ± 1.5^{bc}	80.0 ± 2.0^{ab}
Days to first harvest (DAT)	108.3 ± 2.5^{b}	109.3 ± 2.0^{b}	107.6 ± 2.0^{b}	110.3 ± 1.5^{b}	124.0 ± 1.0^{a}	108.3 ± 2.5^{b}	109.3 ± 2.0^{b}	107.6 ± 2.0^{b}	110.3 ± 1.5^{b}	124.0 ± 1.0^{a}
Date of peak harvest	29/12/2023	3/1/2024	23/1/2024	16/2/2024	16/2/2023	29/12/2023	3/1/2024	23/1/2024	7/2/2024	16/2/2023
Days to peak harvest (DAT)	114.6 ± 1.5^{e}	129.3 ± 2.0^{b}	119.6 ± 0.5^{d}	133.6 ± 1.5^{a}	124.0 ± 1.0^{c}	114.6 ± 1.5^{d}	129.3 ± 2.0^{a}	119.6 ± 0.5^{c}	124.6 ± 1.5^{b}	124.0 ± 1.0^{b}
Days to last harvest (DAT)	151.6 ± 1.1^{a}	141.3 ± 0.5^{b}	135.0 ± 0.0^{c}	134.0 ± 1.0^{c}	129.3 ± 0.5^{d}	143.6 ± 1.5^{a}	141.3 ± 0.5^{a}	135.0 ± 0.0^{b}	134.0 ± 1.0^{b}	129.3 ± 0.5^{c}
Harvest duration (days)	43.3 ± 3.5^{a}	32.0 ± 1.7^{b}	27.3 ± 2.0^{bc}	23.6 ± 1.5^{c}	5.3 ± 1.5^{d}	35.3 ± 0.5^{a}	32.0 ± 1.7^{b}	24.0 ± 1.0^{c}	23.6 ± 0.5^{c}	5.3 ± 1.5^{d}
No. of total harvests	6.0 ± 1.0^{a}	4.0 ± 0.0^{b}	3.6 ± 0.5^{b}	2.6 ± 0.5^{bc}	2.0 ± 0.0^{c}	6.0 ± 0.0^{a}	4.0 ± 0.0^{b}	3.0 ± 1.0^{bc}	2.6 ± 0.5^{bc}	2.0 ± 0.0^{c}
Interval between two successive harvests	7.5 ± 0.1^{d}	9.2 ± 0.2^{b}	8.3 ± 0.2^{c}	11.0 ± 0.2^{a}	4.0 ± 0.1^{e}	7.5 ± 0.1^{c}	9.2 ± 0.2^{b}	10.9 ± 0.1^{a}	11.0 ± 0.2^{a}	4.0 ± 0.1^{d}

Values represent mean±standard deviation (SD). Means followed by different lowercase letters within a row for each variety indicate significant differences (Tukey's HSD test, $p < 0.05$). *DAT- Days after transplanting

Specifically, seedlings transplanted on 4 September 2023 demonstrated the longest harvest duration, with WS-909 exhibiting 43.3±3.5 days and Amazing showing 35.3±0.5 days (Table 4). Additionally, number of harvests ranged from 2 to 6.0±1.0 for both varieties. Notably, maximum number of harvests for WS-909 (6.0±1.0) and Amazing (6.0±0.0) occurred with seedlings transplanted on 4 September 2023. Consequently, it is evident that delays in transplanting correlate with reduced harvest duration, a decrease in total number of harvests, and, as a result, a decline in overall yield. This suggests that optimal transplanting times are crucial for maximizing yield and extending the harvest period. As demonstrated in this study, early transplanting allows for extended harvest periods and increased harvest frequencies, thereby enhancing overall yield. These findings underscore the importance of aligning transplanting schedules with favorable environmental conditions to maximize cauliflower production.

CONCLUSION

Our findings demonstrate that transplanting dates significantly influence growth dynamics, yield attributes, and harvest duration. The transplanting on 4 September, 2023 resulted in highest curd weight, superior marketable yield, and an extended harvest period, while delays in transplanting led to a progressive decline in productivity and quality. Despite the substantial temperature fluctuations within the passive solar greenhouse, curd formation was achieved across all transplanting dates, confirming the feasibility of winter cauliflower production in this high-altitude environment. However, increased temperatures within the greenhouse also contributed to fuzziness in harvested curds, underscoring need for improved microclimate management strategies. Thus, it is recommended that transplanting of cauliflower should be done in early-September to maximize yield and marketable quality. Late transplanting of cauliflower may facilitate availability of fresh produce during the peak winter months; however, this practice may result in a reduced yield.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Kunzes Dolma: Formal analysis; Investigation; Tsering Stobdan: Conceptualization; Methodology; Supervision; Writing – review and editing; O. P. Chaurasia: Project administration; Resources; Writing – review and editing; Dattatray S. Dhavale: Formal analysis; Investigation; Vishal B. Mhetre: Data curation; Validation; Visualization; Writing – original draft; Writing – review and editing

All authors have read the manuscript and agreed to its content. They have also approved the final version of the manuscript and consent to its submission.

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