



## Mulching and Greenhouse Structure Significantly Impact Spinach Production during Winter in Trans-Himalayan Ladakh, India

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Received: September 23, 2025 Accepted: April 2, 2026

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#### Citation

Dhavale, D.S., Stobdan, T., Chaurasia, O.P. and Mhetre, V.B. 2026. Mulching and greenhouse structure significantly impact spinach production during winter in Trans-Himalayan Ladakh, India. *Annals of Arid Zone* 65(2): 131-141

doi:10.56093/aaz.v65i2.172006

<https://epubs.icar.org.in/index.php/AAZ/article/view/172006>

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**Abstract:** A winter greenhouse experiment was conducted during 2024-2025 in the trans-Himalayan cold-arid region of Leh, Ladakh, to evaluate the combined effects of protected structure type and black polyethylene mulching on the growth and yield of spinach (*Spinacia oleracea* L.). The study compared four protected cultivation systems: a large Ladakh passive solar greenhouse, a small Ladakh greenhouse, a polycarbonate trench greenhouse, and a polyethylene trench greenhouse, each under mulched and non-mulched conditions. Spinach cv. *Pusa Vilayati Palak* was harvested through three successive cuttings taken at the marketable leaf stage, with harvest intervals varying among protected structures due to differences in microclimatic conditions, and key growth and yield parameters were recorded. The large Ladakh greenhouse combined with mulch consistently outperformed other structures, producing the highest cumulative yield (223.4 g plant<sup>-1</sup>; 9.9 kg m<sup>-2</sup>), representing a 53% increase over the corresponding non-mulched treatment. Mulching significantly enhanced plant growth, chlorophyll index, and regrowth capacity across structures, and advanced the first harvest by 2-3 days. In the polycarbonate trench greenhouse, mulch increased cumulative yield by up to 72%, enabling three successive cuttings. In contrast, the polyethylene trench greenhouse failed to support regrowth beyond the first cutting due to inadequate thermal insulation under peak winter conditions. Overall, mulching increased total spinach yield by 37.5-69.7%, depending on the greenhouse structure and cutting stage from I to III. The results demonstrate that structure-specific protected cultivation combined with mulching is a highly effective strategy for enhancing winter spinach productivity in high-altitude, sub-zero environments.

**Key words:** Ladakh Greenhouse, Trench Greenhouse, Passive solar greenhouse, soil temperature, *Spinacia oleracea*

Low-cost passive solar greenhouses are commonly used in high mountain regions, particularly at elevations above 3,000 m above mean sea level (msl), for growing vegetables during the peak winter months (Stobdan, 2023). However, a significant limitation of these greenhouses is that the temperature inside

often drops to sub-zero degrees Celsius at night in December and January. This restricts cultivation to freeze-tolerant leafy vegetables (Angmo *et al.*, 2019a). Recently, improved passive solar greenhouses have been developed in the trans-Himalayan Ladakh region, allowing for year-round vegetable production without the need for auxiliary heating or cooling. These improved structures differ in size, design, and cladding material, which in turn influence their thermal performance and suitability for winter vegetable cultivation.

To optimize the production of leafy vegetables in these greenhouses, additional strategies such as mulching are essential. Mulching is an important agronomic practice that involves covering the soil surface with organic or synthetic materials to enhance plant growth conditions. This technique improves soil moisture retention, regulates soil temperature, suppresses weed growth, and increases nutrient availability. Among various types of mulch, black polythene mulch has proven particularly effective in modifying the soil microclimate, resulting in better plant growth and higher yields (Choudhary *et al.*, 2022). Studies show that black polythene mulch raises soil temperature and is beneficial for increasing crop productivity in cold mountain regions (Angmo *et al.*, 2019b). Additionally, this mulch effectively suppresses weed growth, reducing competition for nutrients and water, which ultimately enhances plant vigour and productivity.

This study aimed to assess the combined effects of black polythene mulch and greenhouse size on the growth and yield of spinach (*Spinacia oleracea* L.) during the winter months. Specifically, the experiment evaluated spinach performance under different protected cultivation environments, including two passive solar Ladakh greenhouse variants (large and small) and two trench-based greenhouse structures differing in cladding material, under mulched and non-mulched conditions. This study appears to be the first systematic evaluation of mulching techniques and greenhouse size for winter vegetable production under high-mountain cold-region conditions. The experimental workflow involved comparing growth, yield, harvest frequency, and regrowth dynamics of spinach across structures and mulch treatments through

successive winter cuttings, thereby enabling an integrated assessment of structure-mulch interactions under extreme cold conditions. The findings will provide valuable scientific insights into the role of black polythene mulch in spinach production within a greenhouse setting. Furthermore, this research will contribute to the development of optimized cultivation practices for cold desert regions, ensuring sustainable vegetable production and improved resource efficiency.

## Materials and Methods

### *Experimental site and production environments*

The experiment was conducted during the winter season of 2024-2025 at the experimental farm of the Defence Institute of High Altitude Research (DIHAR), Leh, Ladakh, at an elevation of 3,340 m msl (34°08.2'N; 77°34.3'E). Spinach was grown simultaneously in four distinct passive solar greenhouses: the large Ladakh Greenhouse (LGH-90), the Small Ladakh Greenhouse (LGH-32), a Polytrench covered with a polycarbonate sheet (PT-polycarbonate), and a Polytrench covered with a polyethylene sheet (PT-polyethylene). These four greenhouses are situated near each other. LGH-90 and LGH-32 are passive solar greenhouses-oriented east-west, with cement-plastered stone walls on three sides (the east and west walls are 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. The roofs are sloped to the north and covered with a PUF sheet on the north side of the greenhouse. The dimensions of LGH-90 were 27.4 m × 8.2 m, while those of LGH-32 were 9.8 m × 5.5 m. The Polytrench measures 9.14 m in length, 3.05 m in width, and 0.91 m in depth, and is oriented north-south. It features an above-ground tunnel-shaped frame that supports the covering material. The PT-Polycarbonate greenhouse is covered with a 16-mm triple-layer polycarbonate sheet, while the PT-Polyethylene greenhouse uses a clear polyethylene sheet as cladding material.

Continuous monitoring of both internal and external weather parameters was conducted using automatic digital thermo-hygrometers (model 445702, Extech Instruments) positioned at canopy height within each greenhouse. Light intensity was measured using a calibrated

digital lux meter (EXTECH Instruments Light Meter, Taiwan) at hourly intervals from 06:00 to 18:00 h on the 20<sup>th</sup> day of each month (October, November, December, and January) during the winter cropping period. Observations were recorded under open-field conditions and inside each protected structure. The sensor was positioned at canopy height and measurements were taken under clear sky conditions to minimize cloud-induced variability. The selected observation dates were considered representative of monthly radiation availability during winter. Light intensity data were used to compare diurnal radiation patterns and relative light transmission among protected structures in relation to spinach growth and yield performance. Additionally, a soil thermometer (Omsons Labs, India) was used to measure daily soil temperatures within the production environments. Data on temperature, relative humidity, and soil temperature were recorded at regular intervals, as detailed in Table 1.

#### *Plant material and experimental design*

Seeds of the spinach variety 'Pusa Vilayati Palak' sourced from the ICAR-Indian Agricultural Research Institute, New Delhi were sown during the first week of October 2024. Healthy seedlings were grown in a passive solar greenhouse before being transplanted into four different types of protected structures on October 19, 2024. Each structure included two treatment conditions: mulched beds covered with black polyethylene mulch and non-mulched (bare soil) beds. The mulch was applied to the flat beds just before transplanting, with planting holes spaced 15 cm apart, resulting in a density of 44.4 plants m<sup>-2</sup>. Each treatment replicate consisted of a fixed plot area within each protected structure. The plot size per replicate varied according to greenhouse type: 2.925 m<sup>2</sup> in the large Ladakh greenhouse (LGH-90), 1.575 m<sup>2</sup> in the small Ladakh greenhouse (LGH-32), and 2.205 m<sup>2</sup> in both polycarbonate and polyethylene trench greenhouses. Based on plant spacing, each replicate consisted of 130 plants in LGH-90, 70 plants in LGH-32, and 98 plants in trench greenhouses. Each treatment was replicated three times using a factorial randomized block design (FRBD), incorporating two factors: structure type (four levels) and mulch treatment (two levels: mulch and non-mulch).

All agronomic practices, such as irrigation and weeding, were consistently applied across all treatments and structures. Farmyard manure (FYM) was incorporated into the soil at a rate of 3 kg m<sup>-2</sup> during bed preparation. Flood irrigation was provided weekly during the initial establishment phase and subsequently every two weeks. A total of two weeding operations were conducted throughout the experimental period. Additionally, no chemical pesticides or fertilizers were used in this study. The research included up to three successive harvests, conducted at regular intervals once the plants reached optimal marketable leaf size.

#### *Determination of plant growth and yield traits*

At the time of harvesting, plant growth parameters were recorded from five randomly selected plants plot<sup>-1</sup>. The key traits assessed included plant height (measured from the soil surface to the tip of the longest leaf), stem girth (measured at the base of the stem using a vernier caliper), and the total number of leaves. These measurements followed established procedures. The chlorophyll index of the leaves was evaluated using the SPAD measurement technique (Chlorophyll Meter SPAD-502 Plus, Konica Minolta, Japan) on fully expanded upper leaves. Additionally, the fresh weight of the harvested leaves from each plant was measured using a digital weighing scale during each harvesting session. The results were expressed as both yield (g) plant<sup>-1</sup> and yield (kg) m<sup>-2</sup>. The duration from transplanting to each harvest date was also recorded. To minimize variability due to transpiration or wilting, all measurements were taken during the early morning hours.

The data were compiled and analyzed using R software (version 4.2.2). A two-way analysis of variance (ANOVA) was performed to assess the main effects of structure type and mulching on various growth and yield parameters. The statistical model included structure and mulch as fixed effects, while replication was treated as a random effect. Mean comparisons were conducted using the Least Significant Difference (LSD) test, with a significance level set at 5% ( $p \leq 0.05$ ). The results are presented as mean  $\pm$  standard error, and treatment means were categorized using letter-based significance notation to indicate differences both within and between the examined factors.

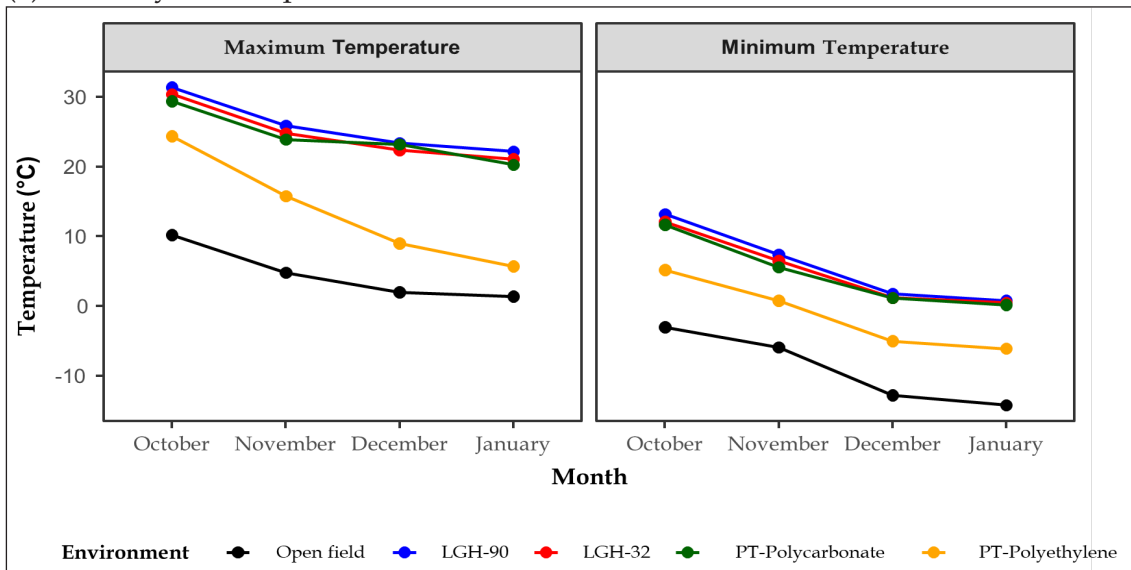
**Results and Discussion**

*Microclimatic modulations in protected structures*

During the winter spinach growing season from October 2024 to January 2025, significant variations were observed between internal and external weather parameters across various protected cultivation structures in Leh, Ladakh (Table 1; Fig.1).

Regulating temperature is crucial for protected cultivation in high mountain regions that experience sub-zero night temperatures. Throughout all structures and months, the internal maximum (Tmax) and minimum (Tmin) temperatures were consistently higher than those recorded outside (Fig. 1). For example, in the LGH-90 structure during December, the average internal Tmax and Tmin were  $23.4 \pm 1.8^\circ\text{C}$  and  $1.8 \pm 1.8^\circ\text{C}$ , respectively, while

(a) Monthly air temperature trends



(b) Monthly soil temperature trends

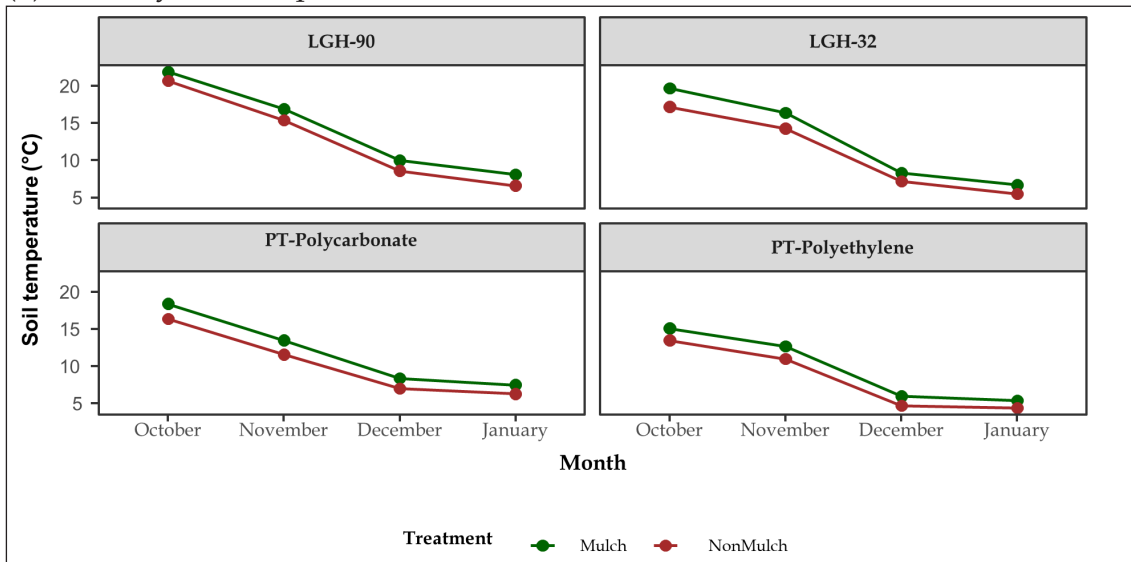


Fig. 1. Seasonal variation in air and soil temperature under open-field and different protected cultivation structures during winter spinach cultivation in the trans-Himalayan Ladakh region.

Seasonal trends in (a) air temperature and (b) soil temperature recorded under open-field conditions and different protected cultivation structures during the winter cropping season (October-January) in Leh, Ladakh. Air temperature data represent monthly mean maximum (Tmax) and minimum (Tmin) values for the open field and greenhouse environments, while soil temperature data show mean root-zone temperatures under mulched (black polyethylene mulch) and non-mulched conditions inside protected structures. The protected structures include a large Ladakh greenhouse (LGH-90), a small Ladakh greenhouse (LGH-32), a polycarbonate trench greenhouse (PT-Polycarbonate), and a polyethylene trench greenhouse (PT-Polyethylene).

Table 1. Relative humidity data of open field and greenhouse during cropping seasons in the trans-Himalayan Ladakh region

Condition	Month	RHmax (%)	RHmin (%)
Open field	October	38.1±12.0	18.4±7.2
	November	31.6±1.5	15.9±1.8
	December	40.9±5.9	23.2±4.5
	January	43.5±3.1	19.4±6.0
LGH-90	October	56.8±1.8	22.1±1.7
	November	57.2±2.1	20.0±1.3
	December	56.9±2.0	19.9±1.0
	January	56.2±1.7	19.6±1.4
LGH-32	October	55.8±2.3	20.7±1.7
	November	55.5±2.3	17.9±1.5
	December	55.4±2.3	17.6±1.2
	January	54.7±2.1	16.9±1.4
PT-Polycarbonate	October	50.6±2.2	17.6±0.9
	November	54.4±3.3	24.3± 4.5
	December	59.8±2.0	30.7± 2.6
	January	64.5±3.0	34.9± 2.6
PT-Polyethylene	October	58.6±2.5	27.6±3.2
	November	52.9±2.4	19.4±2.1
	December	58.2±3.9	29.6±3.9
	January	61.7±1.4	32.3±3.0

\*Values are expressed as Mean ± Standard Deviation (SD).

RHmax and RHmin- Maximum and minimum monthly average relative humidity, respectively; LGH-90: Ladakh greenhouse (90'×27'×9'); LGH-32: Ladakh greenhouse (32'×18'×8'); PT Polycarbonate- Polycarbonate trench greenhouse (30'×18'×3'); PT-Polyethylene- Polyethylene trench greenhouse (30'×18'×3')

the external temperatures were 2.0±2.6°C and -12.8±2.2°C. The larger greenhouse remained warmer than the smaller one, which aligns with earlier findings (Dolma *et al.*, 2023). Additionally, the Polytrench covered with polyethylene was significantly colder than the one covered with polycarbonate due to faster radiative heat loss from polyethylene at night.

Soil temperature is a critical factor affecting root activity, nutrient uptake, and plant growth in cold conditions. Throughout the year, mulched beds consistently recorded higher soil temperatures compared to non-mulched beds across all structures (Fig. 1). The average temperature difference due to mulch ranged from 1.0±0.2°C to 2.5±0.9°C, demonstrating the thermal benefits of black polyethylene mulch. Mulching helps reduce heat loss through radiation and enhances heat absorption during the day, thereby extending root activity and nutrient uptake during cold spells (Kader *et al.*, 2017).

Relative humidity inside protected structures exhibited clear seasonal and structural variations during the winter cropping period (October 2024 to January 2025). Across all structures, mean monthly maximum RH increased progressively from October to January, while minimum RH showed a relatively narrower range, reflecting the buffering effect of protected environments compared to open-field conditions (Table 1). For example, the polyethylene trench greenhouse consistently showed higher RH, especially during December and January (mean max RH 58.2-61.7%), which can be attributed to reduced ventilation and lower heat retention, leading to moisture accumulation. However, excessively high RH in this structure likely contributed to reduced plant vigour and poor regrowth, particularly during later cuttings. Moderate RH levels maintained in the large Ladakh greenhouse (LGH-90) appear agronomically favorable, as adequate humidity reduces transpirational stress while minimizing disease risk, thereby supporting sustained leaf growth and regrowth during successive cuttings.

Similar beneficial effects of balanced RH under protected cultivation have been reported for winter leafy vegetables (Drost *et al.*, 2017; Sanders and Markhart, 2023).

Light intensity followed a distinct diurnal and seasonal pattern, with peak values consistently recorded between 12:00 and 13:00 h, and sharp declines during early morning and late evening hours (Fig. 2). Across all observation dates, the open field received the highest light intensity, reaching 1012 lux in October, followed by a gradual decline to 742 lux in January, reflecting reduced solar elevation and day length during winter. Among protected structures, LGH-90 consistently transmitted higher light levels than other greenhouses, recording midday peaks of 652 lux (October) and 447 lux (January). In contrast, LGH-32 exhibited the lowest light transmission, particularly during December and January, where peak values declined to 393-379 lux, indicating increased structural shading and reduced solar penetration. The polycarbonate trench greenhouse showed intermediate light transmission, while the polyethylene trench greenhouse displayed relatively higher diffuse light, particularly during winter months. However, despite higher transmitted light,

the polyethylene structure failed to support multiple harvests due to sub-optimal thermal conditions, underscoring that light availability alone was insufficient to sustain winter spinach productivity under extreme cold conditions. Reduced light intensity during winter likely contributed to slower regrowth rates and lower yields during second and third cuttings, as spinach growth is strongly dependent on photosynthetically active radiation for leaf expansion and biomass accumulation (Boese and Huner, 1990). Similar seasonal declines in light availability under protected cultivation have been reported to limit winter vegetable productivity unless compensated by improved thermal regimes (Gupta and Chandra, 2002; Angmo *et al.*, 2019a).

The integration of passive solar design and mulching created a synergistic effect that maintained both internal air and soil temperatures within the physiological range (5-25°C) suitable for growing spinach throughout most of the winter. Similarly, the relative humidity and light intensity were also within the optimum range required for growth. This approach is expected to enhance enzymatic activity, chlorophyll production,

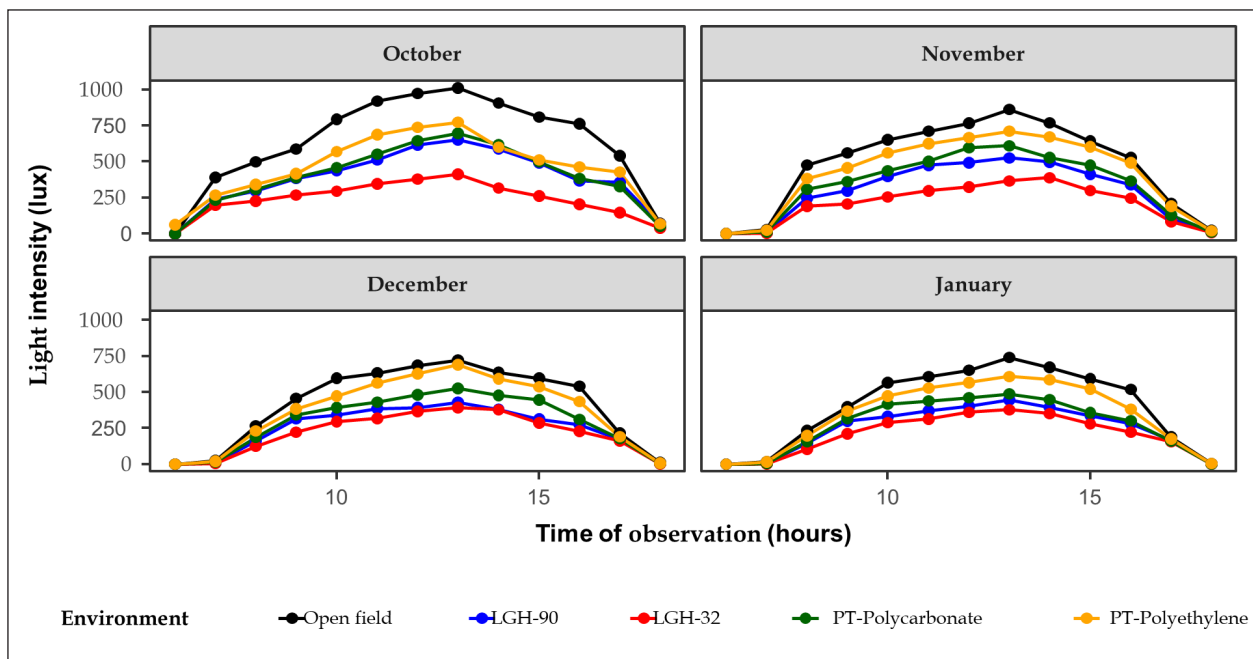


Fig. 2. Diurnal variation in light intensity inside different protected structures during winter months in the trans-Himalayan Ladakh region.

Diurnal light intensity (lux) recorded at hourly intervals (06:00-18:00 h) on the 20th day of October, November, December, and January during the winter cropping season of 2024-25. Measurements were taken in the open field and inside four protected cultivation structures. Values represent instantaneous light intensity recorded using a digital lux meter.

and photosynthetic efficiency, all of which are significantly limited at temperatures below 5°C (Boese and Huner, 1990; Drost *et al.*, 2017). These findings underscore the importance of thermal optimization through structural design and mulching to maximize winter crop yields in cold-arid regions.

*Growth and yield performance of spinach under protected structures and mulch treatments*

The growth and yield characteristics of spinach were significantly influenced by the type of protected structure used and the application of black polyethylene mulch. Data revealed clear trends in plant height, stem girth, number of leaves, chlorophyll index, and yield per plant and per square meter across the three cuttings (Table 2, Fig. 3). Notably, significant interactions between structure and mulch were observed, with mulched treatments consistently outperforming their non-mulched counterparts in all structural environments.

*Cutting I: Early establishment phase:* The first cutting displayed the most vigorous growth across all treatments (Table 2). Spinach plants in the LGH-90 structure with mulch recorded the highest measurements in several growth parameters: plant height (31.7±1.4 cm), stem girth (12.4±0.7 mm), number of leaves (72.4±3.4), chlorophyll index (41.4±4.2), and yield per plant (144.8±21.2 g). In contrast, the corresponding non-mulched treatment in the same structure exhibited significantly lower growth parameters, particularly in yield (83.2±11.2 g per plant), highlighting a 74% increase in yield due to the use of mulch.

Similar trends were observed in other greenhouse structures as well. In the LGH-32, the application of mulch increased yield from 65.6±4.9 g to 96.0±5.2 g plant<sup>-1</sup>. In the PT-Polycarbonate greenhouse, yield improved from 45.6±4.0 g to 72.2±6.6 g. Even though the PT-Polyethylene greenhouse was thermally weaker, it still demonstrated a significant advantage from mulch, with yield rising from 17.4±2.4 g to 25.0±2.7 g plant<sup>-1</sup>.

The improvement in all growth parameters observed in mulched plots can be attributed to better root-zone temperature, enhanced soil moisture retention, and increased metabolic activity during the early stages of crop

establishment (Kader *et al.*, 2017). Additionally, the increased number of leaves and higher chlorophyll index in mulched treatments suggest a more robust photosynthetic system, which supports greater early biomass accumulation (Mon and Oue, 2023). Among the different structures, the LGH-90 showed superior performance, likely due to its higher internal thermal stability and more effective light capture.

*Cutting II: Mid-season phase:* During the second cutting, we observed a noticeable decline in growth performance across all treatments. This decline was attributed to falling temperatures, reduced light intensity, and cumulative cold stress (Table 2). However, the use of mulch continued to show a significant positive impact. Notably, no harvest was possible in the PT-Polyethylene treatment during this phase, indicating its thermal inadequacy in sustaining regrowth during peak winter. In January, minimum temperatures inside the PT-Polyethylene greenhouse reached -6.1°C, which likely caused root zone chilling and metabolic suppression, preventing further vegetative development (Sanders and Markhart, 2023).

*Cutting III: Late-season phase:* The third cutting took place in peak winter conditions in Ladakh, characterized by sub-zero nighttime temperatures (Table 1) and reduced daily solar radiation. These harsh environmental factors resulted in significant decreases in all growth and yield parameters across the experimental structures (Table 2). Nonetheless, the residual benefits of mulching were still evident, particularly in the LGH-90 and PT-Polycarbonate greenhouses, where spinach plants exhibited sustained – albeit reduced – regrowth capacity. Limited plant growth in the absence of mulch may be linked to decreased cell elongation, possibly due to chilling inhibition of auxin flow in the colder root zones during this phase (Sanders and Markhart, 2023). The results demonstrate that, although the LGH-32 was less structurally efficient than its larger counterpart, it still supported three cuttings with satisfactory regrowth when combined with mulch. This approach provides a viable solution for resource-limited protected cultivation systems in high-altitude regions.

In summary, while overall productivity decreased during the third harvest, mulch

played a crucial role in providing residual support for plant physiological functions, especially in structures with moderate thermal protection, such as PT-Polycarbonate. In high-efficiency structures like LGH-90, mulch was more effective in maintaining pigment content and stem vigor than in contributing to the final yield. This suggests that the combination of structural insulation and mulch is most beneficial during the early to mid-phases of winter, whereas structural performance becomes the more significant factor in late winter.

**Yield per square meter:** Yield  $\text{m}^{-2}$  serves as a direct indicator of structural efficiency and cropping potential, reflecting trends observed at the plant level (Fig. 3). Among the structures evaluated, the LGH-90 with mulch achieved the highest total yield of  $9.9 \text{ kg m}^{-2}$  over three cuttings. This was followed by the LGH-32, which yielded  $7.2 \text{ kg m}^{-2}$ , and the PT-Polycarbonate, producing  $5.6 \text{ kg m}^{-2}$ . In contrast, the non-mulched versions of these structures yielded  $6.5$ ,  $4.9$ , and  $3.3 \text{ kg m}^{-2}$ , respectively. The PT-polyethylene performed

considerably worse, primarily due to its inability to support second and third cuttings. Even during the first cutting, its productivity was limited to  $1.1 \text{ kg m}^{-2}$  with mulch and only  $0.8 \text{ kg m}^{-2}$  without it, indicating clear structural limitations (Gupta and Chandra, 2002). Overall, the use of mulch increased total yield by 37.5% to 69.7%, depending on the type of structure and cutting stage.

**Days taken for cuttings:** The number of days taken to reach each harvest stage, which indicates crop maturity and regrowth efficiency, varied significantly based on the type of greenhouse structure and the application of mulch (Table 2). Consistently, mulched treatments matured earlier than their non-mulched counterparts within each structure, highlighting the positive impact of mulching on enhancing thermal conditions and promoting root-zone activity during periods of cold stress.

In the first cutting, spinach grown in the LGH-90 greenhouse with mulch reached harvest maturity in just 28 days after transplanting (DAT). In contrast, the non-mulched conditions

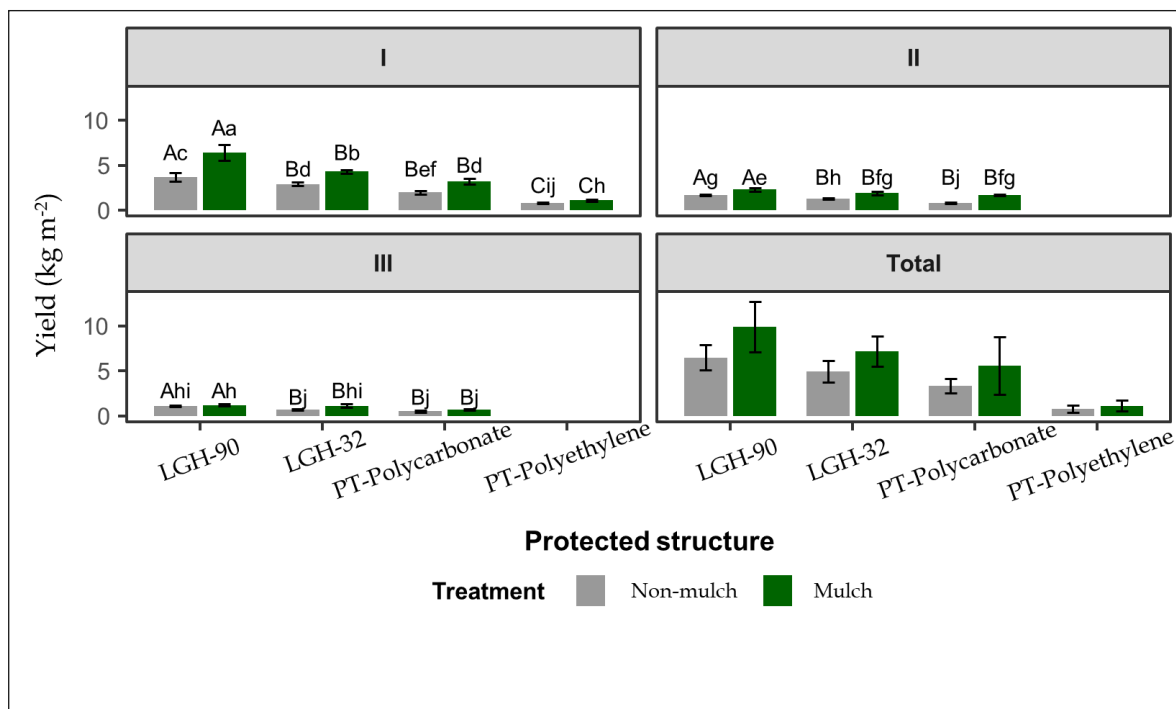


Fig. 3. Effect of black polyethylene mulch on spinach yield ( $\text{kg m}^{-2}$ ) under different protected cultivation structures during the winter season in the trans-Himalayan Ladakh region.

Bars represent mean  $\pm$  standard deviation (SD) for three successive cuttings (I, II, III) and cumulative total yield. Different uppercase letters indicate significant differences among protected structures, while different lowercase letters indicate significant differences between mulch treatments (mulch vs. non-mulch) within the same structure at  $p \leq 0.05$ , according to the Least Significant Difference (LSD) test. No yield was recorded in the polyethylene trench greenhouse beyond the first cutting due to a lack of regrowth.

Table 2. Growth and yield parameters of spinach inside different protected structures during the winter season as influenced by black plastic mulch

Parameters	Cutting	LGH-90		LGH-32		PT polycarbonate		PT polyethylene	
		NM	M	NM	M	NM	M	NM	M
Growth Parameters									
Plant height (cm)	I	28.0±1.2 <sup>Ab</sup>	31.7±1.4 <sup>Aa</sup>	27.9±1.4 <sup>Ab</sup>	30.4±0.7 <sup>Aa</sup>	20.6±1.6 <sup>Bb</sup>	24.7±2.1 <sup>Ba</sup>	7.0±0.8 <sup>Cb</sup>	9.2±1.6 <sup>Ca</sup>
	II	18.1±2.3 <sup>Ab</sup>	24.3±2.2 <sup>Aa</sup>	17.0±1.3 <sup>Ab</sup>	23.4±1.5 <sup>Aa</sup>	16.9±1.4 <sup>Bb</sup>	19.7±1.5 <sup>Ba</sup>	*	*
	III	14.1±1.0 <sup>ABa</sup>	10.0±1.4 <sup>Abb</sup>	7.2±0.4 <sup>Bb</sup>	17.0±1.3 <sup>Ab</sup>	10.9±1.3 <sup>Ab</sup>	13.8±2.0 <sup>Aa</sup>	*	*
Stem girth (mm)	I	8.8±0.8 <sup>Bb</sup>	12.4±0.7 <sup>Ba</sup>	9.8±1.1 <sup>Ab</sup>	13.9±1.0 <sup>Aa</sup>	7.0±0.4 <sup>Cb</sup>	8.2±1.0 <sup>Ca</sup>	5.1±0.5 <sup>Db</sup>	6.0±0.5 <sup>Da</sup>
	II	6.51±0.4 <sup>Ab</sup>	8.0±0.3 <sup>Aa</sup>	6.2±0.5 <sup>Bb</sup>	7.0±0.6 <sup>Ba</sup>	6.3±0.7 <sup>Bb</sup>	7.1±0.6 <sup>Ba</sup>	*	*
	III	5.8±0.5 <sup>Ab</sup>	6.5±0.6 <sup>Aa</sup>	6.0±0.3 <sup>Ab</sup>	6.5±0.6 <sup>Aa</sup>	4.7±0.7 <sup>Bb</sup>	5.8±0.7 <sup>Ba</sup>	*	*
No. of leaves	I	61.4±5.0 <sup>Ab</sup>	72.4±3.4 <sup>Aa</sup>	51.8±4.0 <sup>Bb</sup>	62.0±4.7 <sup>Ba</sup>	38.2±3.7 <sup>Cb</sup>	50.6±2.1 <sup>Ca</sup>	27.8±2.9 <sup>Db</sup>	31.8±3.4 <sup>Da</sup>
	II	40.4±4.0 <sup>Aa</sup>	40.4±4.0 <sup>Aa</sup>	30.8±1.8 <sup>Bb</sup>	35.0±2.7 <sup>Ba</sup>	28.8±2.2 <sup>Bb</sup>	36.2±2.3 <sup>Ba</sup>	*	*
	III	14.6±0.6 <sup>Bb</sup>	18.6±1.5 <sup>Ba</sup>	18.2±2.2 <sup>Ab</sup>	21.4±3.9 <sup>Aa</sup>	9.6±1.3 <sup>Bb</sup>	19.6±1.3 <sup>Ba</sup>	*	*
Chlorophyll index	I	35.3±4.0 <sup>Ab</sup>	41.4±4.2 <sup>Aa</sup>	30.5±2.0 <sup>Bb</sup>	36.7±1.4 <sup>Ba</sup>	31.1±2.2 <sup>Bb</sup>	36.4±3.5 <sup>Ba</sup>	30.7±1.4 <sup>Bb</sup>	32.1±3.5 <sup>Ba</sup>
	II	29.4±2.9 <sup>Bb</sup>	35.4±2.3 <sup>Ba</sup>	34.0±1.6 <sup>Ab</sup>	36.9±2.5 <sup>Aa</sup>	32.0±2.3 <sup>ABb</sup>	34.3±3.0 <sup>ABa</sup>	*	*
	III	26.3±3.0 <sup>Bb</sup>	29.8±3.1 <sup>Ba</sup>	30.5±1.3 <sup>Ab</sup>	31.5±1.7 <sup>Aa</sup>	29.3±2.5 <sup>Ab</sup>	32.0±2.3 <sup>Aa</sup>	*	*
Yield/plant (g)	I	83.2±11.2 <sup>Ab</sup>	144.8±21.2 <sup>Aa</sup>	65.6±4.9 <sup>Bb</sup>	96.0±5.2 <sup>Ba</sup>	45.6±4.0 <sup>Cb</sup>	72.2±6.6 <sup>Ca</sup>	17.4±2.4 <sup>Db</sup>	25.0±2.7 <sup>Da</sup>
	II	38.4±2.2 <sup>Ab</sup>	52.6±3.5 <sup>Aa</sup>	29.0±3.1 <sup>Bb</sup>	65.6±4.9 <sup>Bb</sup>	16.8±2.6 <sup>Cb</sup>	39.2±2.8 <sup>Ca</sup>	*	*
	III	24.0±1.7 <sup>Ab</sup>	26.0±1.6 <sup>Aa</sup>	15.2±1.8 <sup>Bb</sup>	24.0±3.3 <sup>Ba</sup>	11.2±1.5 <sup>Cb</sup>	15.4±2.4 <sup>Ca</sup>	*	*
	Total	145.6±30.9	223.4±62.4	109.8±26.0	161.8±37.5	73.6±18.5	126.8±28.5	17.4	25.0
Days taken for cuttings									
Days taken (#DAT)	I	31	28	33	31	37	35	70	66
	II	61	59	65	62	72	68	*	*
	III	99	95	102	99	104	101	*	*

Values are expressed as Mean ± Standard Deviation followed by significance letters. Values followed by different letters within a column indicate significant differences among treatments at  $p \leq 0.05$  according to the Least Significant Difference (LSD) test for each factor. The uppercase letters denote significant differences among Structures ( $p < 0.05$ ) while the lowercase letters show significant differences among Treatments ( $p < 0.05$ ).

\*No further harvests were possible after 1<sup>st</sup> cutting in the polyethylene trench greenhouse.

GH - Type of greenhouse structure; M - mulch treatment, NM - Non-mulch treatment; LGH-90: Ladakh greenhouse (90'×27'×9'); size of plot- 1.95 m × 1.5 m (2.925 m<sup>2</sup>); LGH-32: Ladakh greenhouse (32'×18'×8'), size of plot- 1.5 m × 1.05 m (1.575 m<sup>2</sup>); PT Polycarbonate- Polycarbonate trench greenhouse (30'×18'×3'), size of plot- 2.1 m × 1.05 m (2.205 m<sup>2</sup>); PT Polyethylene - Polyethylene trench greenhouse (30'×18'×3'), size of plot- 2.1 m × 1.05 m (2.205 m<sup>2</sup>); #DAT - Days after transplanting; Plant spacing- 15 cm × 15 cm; Total number of plants/m<sup>2</sup>: 44.4; Date of transplanting: 19.10.2024

took 31 DAT days, indicating a 3-day advancement due to mulching. This trend was also observed in other greenhouses. The PT-polyethylene structure demonstrated late maturity, requiring 66 to 70 DAT days to reach the first cutting stage, regardless of whether mulch was applied. Additionally, second and subsequent cuttings were not obtained in this structure. This delay can be attributed to its poor insulation, which was inadequate for raising internal and soil temperatures necessary for early vegetative growth.

These results indicate that mulch not only accelerates initial maturity but also shortens the regrowth cycle between cuttings by preserving soil warmth, particularly in less insulated structures (Kader *et al.*, 2017; Lehtilä *et al.*, 2023).

### Practical feasibility and economic considerations of protected spinach production

Although the present study did not include a formal economic analysis, the observed yield responses and harvest continuity provide useful insights into the practical feasibility of adopting different protected cultivation systems for winter spinach production in cold-arid regions. The large Ladakh greenhouse with polycarbonate cladding, particularly when combined with black polyethylene mulch, recorded the highest cumulative yield (9.9 kg m<sup>-2</sup>), representing a 53% increase over the non-mulched treatment and enabling three successive winter harvests under sub-zero external conditions. Such yield stability during winter, when open-field cultivation

is not feasible, substantially enhances crop availability and market value. Polycarbonate-clad structures entail higher initial capital investment compared to polyethylene-covered trench systems; however, their superior thermal insulation, durability, and longer service life make them more suitable for multi-season use in high-altitude environments. The consistent regrowth and reduced crop failure risk observed in these structures suggest that the higher upfront cost can be offset over time through increased productivity, extended harvest duration, and reduced replanting frequency. In contrast, polyethylene trench greenhouses, despite lower construction costs, failed to support regrowth beyond the first cutting, limiting their economic viability for multi-harvest leafy vegetable production during peak winter. Mulching further improved system efficiency by increasing total yield by 37.5-69.7%, accelerating crop maturity by 2-3 days, and reducing weed pressure, thereby lowering labor inputs associated with weeding and crop management. From a sustainability perspective, the integration of energy-efficient passive solar structures with mulching minimizes dependence on external energy sources and enhances resource-use efficiency, aligning well with the constraints of cold desert farming systems. Overall, the results indicate that structure-specific selection combined with low-cost agronomic interventions such as mulching offers a technically feasible and practically sustainable strategy for enhancing winter vegetable production in high-altitude regions.

## Conclusions

This study emphasizes the significant impact of greenhouse structure and black polyethylene mulching on enhancing winter spinach production in high mountain cold regions. Over three successive harvests, the combination of structural microclimate buffering and soil thermal insulation provided by mulch consistently improved growth parameters, chlorophyll content, yield, and harvest frequency. Among the four greenhouse structures evaluated, the LGH-90 proved to be the most effective, achieving the highest yield at 223.4 grams per plant (or 9.9 kg m<sup>-2</sup>) and enabling the earliest and most frequent harvests. The LGH-32 and PT-Polycarbonate structures also performed well, particularly

when used with mulch. In contrast, the PT-polyethylene greenhouse was thermally inadequate, supporting only a single harvest and lacking regrowth potential, even with mulch. Additionally, mulching significantly raised root-zone temperatures, promoted early vegetative growth, and sustained physiological functions during the coldest months. It reduced the days to the first harvest by 2-3 days and allowed for second and third cuttings. Key growth traits, such as plant height, stem girth, number of leaves, and chlorophyll index, were consistently higher in mulched plots, especially during the second and third cuttings when environmental stress was more pronounced. Overall, the findings suggest that a synergistic approach combining climate-resilient greenhouse design with surface mulching can substantially extend the winter growing season, boost productivity, and enhance crop sustainability in extreme environments. For high-altitude regions like Ladakh, where winter production is limited by harsh climatic conditions, larger greenhouses with polycarbonate cladding offer a scalable and energy-efficient solution, especially when integrated with mulching practices.

## Authorship Contribution

Dattatray S. Dhavale - Investigation, Data curation; Tsering Stobdan - Conceptualization, Methodology, Resources, Writing - Review and Editing, Supervision, Project administration; O.P. Chaurasia - Resources, Writing - Review and Editing, Supervision; Vishal B. Mhetre - Formal analysis, Data Curation, Writing - Original Draft.

## Competing Interests

The authors declare no competing interests.

## Acknowledgments

The study was supported by the Defence Research and Development Organisation (DRDO), Ministry of Defence, Government of India.

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