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# Impact of Greenhouse Size on the Growth and Yield of Warm-Season Vegetables During the Summer in Ladakh, India

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### ABSTRACT

No guidelines exist on the size of naturally ventilated passive solar greenhouses in mountain regions, especially above 10,000 feet above mean sea level (AMSL). Two different-sized greenhouses in Ladakh were studied, and it was figured out that a large greenhouse (60 feet in length, 24 feet in width, 9 feet 6 inches in height) was better than a small greenhouse (32 feet in length, 18 feet width, 9 feet 6 inches height) for growing cucumber, capsicum, and brinjal in summer. The mean maximum and minimum temperature of the large greenhouse was 3.6±4.1°C and 1.3±1.6°C warmer in comparison to the small greenhouse. Cucumber was harvested seven days earlier, while capsicum and brinjal were harvested 17 days earlier in the large greenhouse. The marketable fruit numbers in cucumber, capsicum, and brinjal were 50.5 %, 46.9 %, and 67.7 % higher in the large greenhouse. The average marketable fruit yield of cucumber, capsicum and brinjal was 112 %, 55 % and 71.4 % higher in the large greenhouse than in the small greenhouse. Hence, large greenhouses are suggested for high-altitude Ladakh regions for growing warm-season crops in summer.

**Keywords:** Capsicum; Cucumber; Brinjal; Greenhouse size; Himalaya; Protected cultivation

## 1. INTRODUCTION

Crop production in the trans-Himalayan Ladakh region is hindered by three major environmental constraints: short-growing length, inadequate precipitation, and poor soil fertility[1]. The most determinant factor is the climate. Only four to five months of the year are congenial for growing crops. Mid-May marks the beginning of the cropping season, while mid-September marks the end of the harvest. Early sowing or transplanting often results in high mortality of seedlings due to spring frost, and late harvesting after mid-September often results in freezing injury. Therefore, limited quantities of vegetables, especially cole and root crops, can be produced in the open field during summer.

Vegetables are harvested from June to September; most of them with bulk production, such as potatoes, onion, cabbage, and carrot, are harvested from late August to September. Therefore, excess vegetable produce is available during this period, while fresh vegetables are scarce in the region in winter. Low temperature limits the optimal production of warm-season vegetables in summer. In open fields, warm-season crops such as brinjal, capsicum, okra, and bitter gourd give very low yields; thus, farmers do not grow these crops on a large scale[2]. Low-cost greenhouses are in demand in the Himalayan regions, especially beyond 10,000 feet above mean sea Level (AMSL), for producing leafy vegetables in winter and seedling production in spring. However, subfreezing temperatures in winter and overheating inside the greenhouse during summer are grave problems that restrict the utility of greenhouses to a few months a year[3]. Recently, improved greenhouses were established for the Ladakh region, where crops can be grown throughout the year with no supplementary cooling or heating. Growing a range of crops like tomato[4] and capsicum[5] in summer, which otherwise is not feasible in the conventionally used passive solar greenhouses, has been established.

Most farmers in mountainous regions prefer small, naturally ventilated greenhouses. In Leh district of Ladakh region most farmers (56.3 %) own low-cost, small-size greenhouses (32 feet x 18 feet), wherein polyethylene is used as the cladding material. However, the high temperatures inside the greenhouse and the chances of damage due to high-speed wind are grave problems in these greenhouses during summer. As a result, most (96.2 %) farmers remove the polyethylene in summer, while the remaining 3.8 % partly remove the polyethylene. Due to these reasons, a majority (91.7 %) of the farmers do not make use of the naturally ventilated greenhouse in summer[3]. Growing vegetables in open fields delays the harvesting of crops, and in the Ladakh region, most crops reach the harvestable stage from late July onwards and

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are harvested before October. Growing vegetables in the greenhouse can advance crop harvesting and increase productivity in high-mountain regions.

The length and width of the naturally ventilated passive solar greenhouse are key elements that govern greenhouse microclimate[6-7]. Most research on the effect of length and width of greenhouse microclimate has been conducted on Chinese solar greenhouses with optimal lengths of 50m to 100m and 5.5 m to 24 m span[7-11]. Besides, most research on the effect of the greenhouse dimension focuses particularly on greenhouse microclimate[6-7]. Limited research trials have been conducted on crop performance under different sizes of greenhouses. Given limited studies on microclimate and vegetable yield in small-size (<100 feet length) naturally ventilated greenhouses in high altitude regions, it is necessary to conduct trials on vegetable yield in different sizes greenhouses that can be used all year round. This knowledge is crucial for farmers in adopting the most suitable greenhouse for vegetable production during summer. As far as we know, there are no established small-size (<100 feet length) solar greenhouse designs for mountainous regions, especially above 10,000 feet AMSL, that can be used for growing vegetables in summer.

## 2. MATERIALS AND METHODS

### 2.1 Study Site and Greenhouse Structures

The trial was conducted at the DRDO-DIHAR Leh Ladakh, India (altitude 10,958 feet AMSL, 34°08.2’N; 77°34.3’E). The study used two passive solar greenhouses differing in length and width. The greenhouse has 2-feet thick stone walls on the east, west, and north sides. The south-facing side is covered with a clear UV-stabilized 16-mm triple-layer polycarbonate panel. Temperature was regulated with manually operated ventilators. No supplementary lighting, heating, and cooling was provided. The temperature inside the greenhouse was recorded daily (Table 1).

### 2.2 Crop and Experimental Design

Cucumber (*Cucumis sativus* L.) cv. Pusa Seedless, capsicum (*Capsicum annum* L.) cv. California Wonder and brinjal (*Solanum melongena* L.) cv. Janak was studied during the year 2020 in the greenhouses and in open fields. Each greenhouse had two rows running parallel to the north wall. The cucumber plants were planted at 45 cm × 45 cm spacing, while capsicum and brinjal were planted at 20 cm × 20 cm spacing. Seedlings were transplanted on 20 March 2020 in greenhouses and 23 May 2020 in the open field. Farmyard manure (4.0 kg per $m^2$) was applied at the time of field preparation. Vermicompost (50 g per plot) was applied at the root zone after the first and second weeding. Irrigation was done by flooding twice a week.

### 2.3 Growth and Yield Attributes

Growth and yield attributes were noted at 30, 60, and 90 days after transplanting (DAT). The date of harvests and yield were recorded. Effects of directional position within the greenhouse were recorded by taking data separately from the two rows of the greenhouse.

## 3. RESULTS AND DISCUSSION

### 3.1 Greenhouse Temperature

The mean maximum and minimum temperatures inside the large greenhouse were 37.8±3.3 and 14.6±2.8°C, respectively, and thus it was 3.6±4.1°C warmer during day time and 1.3±1.6°C warmer at night than the small greenhouse (Table 1). The results demonstrated that the heat storage capacity is more in the large greenhouse.

### 3.2 Growth Attributes

The length and width of the greenhouse showed a major effect on the growth of cucumber (Table 2), capsicum (Table 3), and brinjal (Table 4). The recorded growth parameters were higher in the large greenhouse (Figure. 1). Plant height was 26.1 %, 22.4 %, and 67.3 % higher at 90 DAT in

**Table 1. Temperature inside the two different sizes of greenhouses**

| Month | Maximum temperature (°C) | | | Minimum temperature (°C) | | |
|---|---|---|---|---|---|---|
| | Greenhouse 1 | Greenhouse 2 | Difference | Greenhouse 1 | Greenhouse 2 | Difference |
| **March** | 37.8±7.1 | 33.5±5.2 | 4.6±6.2 | 11.0±2.5 | 8.8±3.8 | 2.2±1.3 |
| **April** | 38.8±5.3 | 34.7±4.2 | 3.2±2.9 | 12.5±1.5 | 10.9±2.2 | 1.8±1.5 |
| **May** | 36.6±2.7 | 31.8±3.3 | 3.5±6.9 | 13.0±2.0 | 11.9±1.9 | 2.0±2.5 |
| **June** | 36.4±2.6 | 34.9±2.9 | 3.3±1.5 | 13.3±2.1 | 12.9±1.9 | 1.9±0.9 |
| **July** | 38.8±3.7 | 35.4±3.9 | 3.5±1.6 | 16.7±2.7 | 15.7±2.0 | 1.0±0.5 |
| **August** | 41.5±1.2 | 36.1±1.1 | 5.4±1.4 | 18.3±0.9 | 17.1±1.1 | 1.2±0.3 |
| **Mean** | 37.8±3.3 | 35.1±3.2 | 3.6±4.1 | 14.6±2.8 | 13.8±2.7 | 1.3±1.6 |

Greenhouse 1: 60 feet ×24 feet × 9 feet 6 inches; Greenhouse 2: 32 feet × 18 feet × 9 feet 6 inches (L×W×H)
Values represented as mean ± SD

**Figure 1. Inside view of the greenhouse (60 feet ×24 feet × 9 feet 6 inches; L×W×H).**

**Table 2. Growth parameters of cucumber cv. Pusa Seedless in greenhouses and open field**

| Parameters | DAT | Greenhouse 1 | | | Greenhouse 2 | | | Open |
|---|---|---|---|---|---|---|---|---|
| | | South | North | Mean | South | North | Mean | |
| Plant height (cm) | 0 | 12.8±1.3 | | | 12.8±1.3 | | | 6.5±0.5 |
| | 30 | $110.8\pm14.1^{**}$ | $91.1\pm9.4^{***}$ | $101.0\pm15.2^{***}$ | $67.5\pm7.4^{***}$ | $54.3\pm21.3^{***}$ | $60.9\pm16.0^{***}$ | 9.5±1.5 |
| | 60 | $120\pm30.2^{*}$ | $152.4\pm14.6^{***}$ | $136.4\pm27.5^{*}$ | $113.4\pm22.7^{*}$ | $100.3\pm9.3^{***}$ | $106.9\pm17.1^{*}$ | 15.5±3.8 |
| | 90 | $216.8\pm11.8^{**}$ | $225.4\pm9.9^{***}$ | $221.1\pm10.8^{***}$ | $193.8\pm4.4_{***}^{***}$ | $157.0\pm5.0_{***}^{***}$ | $175.4\pm20.6^{***}$ | 51.0±5.5 |
| No. of leaves | 0 | 3.3±0.6 | | | 3.3±0.6 | | | 4.7±1.2 |
| | 30 | $21\pm3.0^{**}$ | $18.3\pm0.6^{**}$ | $19.7\pm2.4^{**}$ | $16.7\pm2.5^{**}$ | $12.7\pm4.6^{**}$ | $14.7\pm4.0^{**}$ | 8.3±1.5 |
| | 60 | $34.3\pm7.2^{***}$ | $39.0\pm2.0^{***}$ | $36.7\pm5.4^{***}$ | $19.3\pm6.5^{***}$ | $24.7\pm9.1^{***}$ | $22.0\pm7.6^{***}$ | 9.3±1.5 |
| | 90 | $100.0\pm25.0^{***}$ | $113.5\pm46.5^{***}$ | $106.8\pm34.2^{***}$ | $37.7\pm1.5_{**}^{***}$ | $52.2\pm5.0_{**}^{***}$ | $44.5\pm8.5^{***}$ | 24.5±3.5 |
| Leaf thickness (mm) | 0 | 0.25±0.04 | | | 0.25±0.04 | | | 0.09±0.0 |
| | 30 | 0.26±0.01 | 0.26±0.02 | 0.26±0.01 | 0.25±0.07 | 0.26±0.02 | 0.24±0.04 | 0.48±0.0.1 |
| | 60 | 0.32±0.1 | 0.32±0.00 | 0.32±0.00 | 0.33±0.08 | 0.30±0.05 | 0.32±0.06 | 0.56±0.1 |
| | 90 | 0.30±0.05 | 0.30±0.03 | 0.30±0.05 | $0.26\pm0.01_{*}$ | $0.28\pm0.00_{*}$ | 0.27±0.02 | 0.56±0.1 |
| Stem diameter (mm) | 0 | 2.6±0.1 | | | 2.6±0.1 | | | 4.1±0.0 |
| | 30 | 9.4±0.5 | $9.3\pm0.6^{**}$ | $9.3\pm0.4^{**}$ | 9.0±0.3 | $7.5\pm1.5^{**}$ | $8.3\pm1.2^{**}$ | 5.5±1.5 |
| | 60 | 9.9±0.8 | $9.8\pm0.5^{**}$ | $9.8\pm0.6^{*}$ | 9.4±0.5 | $8.5\pm0.6^{**}$ | $9.0\pm0.7^{*}$ | 6.5±1.5 |
| | 90 | 11.6±0.1 | 10.2±3.3 | 10.9±2.9 | 9.0±0.1 | 9.1±0.4 | 9.1±0.3 | 7.6±1.4 |
| No. of branches | 0 | 0.0 | | | 0.0 | | | 0.0 |
| | 30 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 60 | $2.3\pm0.6^{**}$ | $2.7\pm0.6^{**}$ | $2.5\pm0.5^{**}$ | $1.7\pm0.6^{**}$ | $1.7\pm0.6^{**}$ | $1.7\pm0.5^{**}$ | 0.7±0.6 |
| | 90 | $3.3\pm0.6^{*}$ | $3.7\pm0.6^{**}$ | $3.5\pm0.5^{*}$ | $2.7\pm0.6^{*}$ | $2.3\pm1.2^{**}$ | $2.5\pm0.8^{*}$ | 1.7±0.6 |

Greenhouse 1: 60 feet ×24 feet × 9 feet 6 inches; Greenhouse 2: 32 feet × 18 feet × 9 feet 6 inches (L×W×H)
Date of transplanting: Greenhouse 1 & 2: 20 Mar 2020; Open: 23 May 2020
Values represented as mean ± SD;
*Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$, ***Significant at $p \leq 0.001$, as measured by Independent Student t-test
Superscript: Significantly different between the two greenhouses within the same direction
Subscript: Significantly different between two directions within the same greenhouse

**Table 3. Growth parameters of capsicum cv. California Wonder in greenhouses and open field**

| Parameters | DAT | Greenhouse 1 | | | Greenhouse 2 | | | Open |
|---|---|---|---|---|---|---|---|---|
| | | South | North | Mean | South | North | Mean | |
| Plant height (cm) | 0 | 10.0±0.5 | | | 10.0±0.5 | | | 3.0±0.1 |
| | 30 | 21.4±0.6$^{***}$ | 18.0±3.3$^{***}$ | 19.7±2.9$^{***}$ | 15.1±3.0$^{***}$ | 13.2±1.0$^{***}$ | 14.1±2.2$^{***}$ | 3.5±0.4 |
| | 60 | 50.4±7.6$^{***}$ | 56.1±2.8$^{***}$ | 53.3±6.0$^{***}$ | 26.2±2.0$^{***}$ | 17.3±1.2$^{***}$ | 28.8±4.1$^{***}$ | 13.5±4.1 |
| | 90 | 61.7±9.4$^{**}$ | 62.9±6.2$^{*}$ | 62.3±7.1$^{*}$ | 55.3±2.3$^{*}$ | 46.6±6.4$^{**}$ | 50.9±6.4$^{*}$ | 30.5±8.0 |
| No. of leaves | 0 | 4.3±0.6 | | | 4.3±0.6 | | | 3.7±0.6 |
| | 30 | 12.0±1.0$^{***}$ | 11.7±1.2$^{***}$ | 11.8±1.0$^{***}$ | 9.0±1.0$^{***}$ | 8.3±0.6$^{***}$ | 8.7±0.8$^{***}$ | 5.6±1.2 |
| | 60 | 24.3±6.8$^{***}$ | 27.0±4.4$^{***}$ | 25.7±5.3$^{***}$ | 19.3±2.3$^{***}$ | 17.3±1.2$^{***}$ | 18.3±2.0$^{***}$ | 18.0±1.5 |
| | 90 | 36.0±5.2 | 36.7±1.5 | 36.3±3.4 | 38.0±6.2 | 35.3±1.2 | 36.7±4.3 | 30.0±3.6 |
| Leaf thickness (mm) | 0 | 0.18±0.05 | | | 0.18±0.05 | | | 0.29±0.03 |
| | 30 | 0.23±0.03 | 0.20±0.03 | 0.22±0.03 | 0.23±0.02 | 0.23±0.09 | 0.23±0.06 | 0.42±0.04 |
| | 60 | 0.26±0.04 | 0.26±0.02 | 0.26±0.02 | 0.25±0.03 | 0.24±0.05 | 0.24±0.03 | 0.38±0.08 |
| | 90 | 0.25±0.02$^{***}$ | 0.25±0.01$^{***}$ | 0.25±0.02$^{***}$ | 0.22±0.02$^{***}$ | 0.19±0.02$^{***}$ | 0.21±0.02$^{***}$ | 0.31±0.01 |
| Stem diameter(mm) | 0 | 1.4±0.1 | | | 1.4±0.1 | | | 1.1±0.1 |
| | 30 | 3.9±0.3$^{***}$ | 3.6±0.4$^{***}$ | 3.7±0.4$^{***}$ | 2.9±0.3$^{***}$ | 2.3±0.3$^{***}$ | 2.6±0.4$^{***}$ | 2.2±0.8 |
| | 60 | 6.9±0.7$_{*}^{***}$ | 8.2±0.4$_{*}^{***}$ | 7.5±0.9$^{***}$ | 4.8±0.6$^{***}$ | 4.7±0.4$^{***}$ | 4.8±0.5$^{***}$ | 4.8±0.3 |
| | 90 | 8.9±0.8$^{***}$ | 9.10±0.8$^{***}$ | 9.0±0.7$^{***}$ | 6.8±0.4$^{***}$ | 7.0±0.2$^{***}$ | 6.9±0.3$^{***}$ | 7.3±0.2 |
| No. of branches | 0 | 0.0 | | | 0.0 | | | 0.0 |
| | 30 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 60 | 1.3±0.6$^{***}$ | 2.0±1.7$^{***}$ | 1.7±1.2$^{***}$ | 0.0±0.0$^{***}$ | 0.0±0.0$^{***}$ | 0.0$^{***}$ | 0.0 |
| | 90 | 3.7±0.6$^{*}$ | 3.0±1.0$^{*}$ | 3.8±0.8$^{*}$ | 2.3±0.6$^{*}$ | 2.7±0.6$^{*}$ | 2.5±0.5$^{*}$ | 0.6±0.5 |

Greenhouse 1: 60 feet ×24 feet × 9 feet 6 inches; Greenhouse 2: 32 feet × 18 feet × 9 feet 6 inches (L×W×H)
Date of transplanting: Greenhouse 1 & 2: 20 Mar 2020; Open: 23 May 2020
*Significant at $p \leq 0.05$, **Signigicant at $p \leq 0.01$, *** Significant at $p \leq 0.001$ between the two greenhouses within the same direction as measured by Independent Student t-test

**Table 4. Growth parameters of brinjal cv. Janak grown in greenhouses and open field**

| Parameters | DAT | Greenhouse 1 | | | Greenhouse 2 | | | Open |
|---|---|---|---|---|---|---|---|---|
| | | South | North | Mean | South | North | Mean | |
| Plant height (cm) | 0 | 11.6±0.7 | | | 11.6±0.7 | | | 3.2±0.1 |
| | 30 | 16.8±4.2$^{***}$ | 15.1±0.3$^{*}$ | 16.0±2.8$^{**}$ | 12.5±1.4$^{***}$ | 12.1±1.5$^{*}$ | 12.3±1.3$^{**}$ | 4.5±0.5 |
| | 60 | 55.6±6.0$^{***}$ | 56.8±2.6$^{***}$ | 56.2±4.2$^{***}$ | 32.0±2.3$^{***}$ | 21.7±3.1$^{***}$ | 26.9±6.3$^{***}$ | 14.7±6.0 |
| | 90 | 74.2±5.2$^{***}$ | 79.5±3.7$^{***}$ | 76.8±5.0$^{***}$ | 51.9±3.4$^{***}$ | 39.8±3.4$^{***}$ | 45.9±7.3$^{***}$ | 26.7±0.9 |
| No. of leaves | 0 | 4.7±0.6 | | | 4.6±0.7 | | | 3.0±0.0 |
| | 30 | 10.3±3.8$^{**}$ | 8.3±1.5$^{*}$ | 9.3±2.8$^{*}$ | 7.0±1.0$^{**}$ | 6.0±1.0$^{*}$ | 6.5±1.0$^{*}$ | 3.7±0.6 |
| | 60 | 27.0±6.1$^{***}$ | 30.3±6.0$^{***}$ | 28.7±5.7$^{***}$ | 18.0±3.6$^{***}$ | 14.3±2.1$^{***}$ | 16.2±3.3$^{***}$ | 5.3±1.5 |
| | 90 | 48.7±4.5$^{***}$ | 36.7±4.9$^{***}$ | 42.7±7.8$^{***}$ | 33.7±4.6$^{***}$ | 26.3±1.2$^{***}$ | 30.0±5.0$^{***}$ | 11.7±3.8 |
| Leaf thickness (mm) | 0 | 0.25±0.05 | | | 0.25±0.05 | | | 0.20±0.06 |
| | 30 | 0.27±0.02 | 0.26±0.01 | 0.26±0.02 | 0.30±0.04 | 0.28±0.05 | 0.29±0.04 | 0.31±0.02 |
| | 60 | 0.28±0.01 | 0.29±0.03 | 0.28±0.02 | 0.32±0.04 | 0.30±0.03 | 0.31±0.03 | 0.42±0.02 |
| | 90 | 0.27±0.05 | 0.28±0.02 | 0.28±0.03 | 0.27±0.01 | 0.23±0.01 | 0.25±0.03 | 0.43±0.03 |
| Stem diameter (mm) | 0 | 1.7±0.1 | | | 1.7±0.01 | | | 1.1±0.1 |
| | 30 | 4.9±1.3$^{***}$ | 4.8±0.1$^{***}$ | 4.8±0.8$^{***}$ | 3.6±0.4$^{***}$ | 2.4±0.2$^{***}$ | 3.0±0.7$^{***}$ | 1.3±0.0 |
| | 60 | 7.43±1.76 | 9.0±0.9 | 8.3±1.5 | 8.9±1.1 | 6.8±0.3 | 7.8±1.7 | 4.6±0.6 |
| | 90 | 9.8±1.0 | 9.9±1.06 | 10.0±0.9 | 10.7±1.10 | 9.8±1.1 | 10.2±1.1 | 5.5±0.3 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No. of branches** | 0 | 0.0 | | | 0.0 | | | 0.0 |
| | 30 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 60 | $2.3\pm0.6$ | $1.6\pm0.6$ | $2.6\pm0.6$ | $1.7\pm0.6$ | $1.3\pm0.6$ | $1.5\pm0.5$ | $0.7\pm0.5$ |
| | 90 | $3.7\pm0.6$ | $2.7\pm1.2$ | $3.2\pm1.0$ | $2.7\pm0.6$ | $2.0\pm0.0$ | $2.3\pm0.5$ | $1.6\pm0.7$ |

Greenhouse 1: 60 feet ×24 feet × 9 feet 6 inches; Greenhouse 2: 32 feet × 18 feet × 9 feet 6 inches (L×W×H)
Date of transplanting: Greenhouse 1 & 2: 20 Mar 2020; Open: 23 May 2020
*Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$, ***Significant at $p \leq 0.001$ between the ywo greeenhouses within the same directions as measured by Independent Student t-test

**Table 5. Marketable yield of cucumber, capsicum, and brinjal in greenhouses and in open field**

| Crop | Green house/ open | First harvest | Last harvest | No. of harvests | No. of fruit per plant | | | Yield per plant (kg) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | North | South | Mean | North | South | Mean |
| Cucumber cv. Pusa Seedless | Green house1 | 29-04 | 10-08 | 10 | $14.1\pm1.1^{***}$ | $16.3\pm0.7^{***}$ | $15.2\pm0.9^{***}$ | $2.1\pm0.2_{**}^{***}$ | $2.1\pm0.1_{**}^{***}$ | $2.1\pm0.1^{***}$ |
| | Green house2 | 06-05 | 10-08 | 9 | $11.6\pm2.4_{***}^{***}$ | $8.6\pm1.2_{***}^{***}$ | $10.1\pm1.8^{***}$ | $1.19\pm0.11_{***}^{***}$ | $0.79\pm0.06_{***}^{***}$ | $0.99\pm0.08^{***}$ |
| | Open | 29-07 | 20-09 | 5 | - | - | $0.6\pm0.1$ | - | - | $0.11\pm0.03$ |
| Capsicum cv. California Wonder | Green house1 | 26-06 | 10-08 | 7 | $4.6\pm0.4^{***}$ | $4.8\pm0.3^{***}$ | $4.7\pm0.4^{***}$ | $0.32\pm0.03^{***}$ | $0.31\pm0.02^{***}$ | $0.31\pm0.02^{***}$ |
| | Green house2 | 13-07 | 10-08 | 5 | $3.2\pm0.3^{***}$ | $3.1\pm0.3^{***}$ | $3.2\pm0.3^{***}$ | $0.20\pm0.02^{***}$ | $0.19\pm0.02^{***}$ | $0.20\pm0.02^{***}$ |
| | Open | 16-9 | 20-9 | 2 | - | - | $0.2\pm0.1$ | - | - | $0.06\pm0.0$ |
| Brinjal cv. Janak | Green house1 | 03-07-20 | 10-08 | 6 | $2.9\pm0.2^{***}$ | $2.6\pm0.2^{***}$ | $2.8\pm0.02^{***}$ | $0.37\pm0.03_{*}^{**}$ | $0.35\pm0.03_{*}^{***}$ | $0.36\pm0.03^{***}$ |
| | Green house2 | 20-07 | 10-08 | 3 | $2.4\pm0.2_{***}^{***}$ | $1.0\pm0.0_{***}^{***}$ | $1.7\pm0.0^{***}$ | $0.31\pm0.05_{***}^{**}$ | $0.10\pm0.02_{***}^{***}$ | $0.21\pm0.04^{***}$ |
| | Open | 16-9 | 20-9 | 2 | - | - | $1.0\pm0.2$ | - | - | $0.07\pm0.03$ |

Greenhouse 1: 60 feet ×24 feet × 9 feet 6 inches; Greenhouse 2: 32 feet × 18 feet × 9 feet 6 inches (L×W×H)
Date of transplanting: Greenhouse 1 & 2: 20 Mar 2020; Open: 23 May 2020
*Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$, ***Significant at $p \leq 0.001$, as measured by Independent Student t-test
Superscript: significantly different between the two greenhouses within the same direction
Subscript: significantly different between the two directions within the same greenhouse

cucumber, capsicum, and brinjal, respectively, in the large greenhouse. The number of leaves in cucumber and brinjal was 140 % and 42.3 % higher in the large greenhouse. Stem diameter was 30.0 % higher in capsicum in the large greenhouse. In the large greenhouse, the number of branches was 40.0 %, 52.0 %, and 39.0 % higher in cucumber, capsicum, and brinjal. The three selected crops are warm-season crops, and lower growth in the small greenhouse may be the result of less favorable temperatures. The optimum temperature for the growth ranged from 25°C for cucumber[12], 20-25°C for capsicum[13], and 21-29°C for brinjal[14].

### 3.3 Marketable and Early Yield

Early and higher marketable yield was recorded in the large greenhouse. Cucumber was harvested seven days earlier, while capsicum and brinjal were harvested 17 days earlier than the small greenhouse (Table 5). Fruits were harvested more frequently in the large greenhouse. The number of harvests of cucumber, capsicum, and brinjal were 10, 7, and 6 against 9, 5, and 3 in the small greenhouse. The number of marketable fruits in cucumber, capsicum, and brinjal was 50.5 %, 46.9 %, and 64.7 % higher in the large greenhouse. The mean marketable yield of cucumber was 2.1±0.1 kg per plant in the large greenhouse, which was significantly higher than that of the small greenhouse (0.99±0.08 kg per plant). The marketable weight of capsicum was 0.31±0.02 kg per plant in the large greenhouse as against 0.2±0.02 kg per plant in the small greenhouse. Similarly, the mean marketable yield of brinjal was 0.36±0.03 kg per plant in the large greenhouse as against 0.21±0.04 kg per plant in the small greenhouse.

### 3.4 Effects of Greenhouse Directional Position on Yield

The directional position within the greenhouse did not significantly affect the number of fruits and the yield in the large greenhouse (Table 5). However, a significantly greater number of fruits per plant was recorded in cucumber and brinjal on the north side of the small greenhouse. Similarly, higher cucumber (50.6 %) and brinjal (210 %) yields were recorded on the north side of the small greenhouse. More fruit and the higher marketable yield on the north side of the small greenhouse may be due to the stone wall at the north side that acts as a thermal mass. Therefore, the crop's directional position significantly affects the number and marketable fruit yield per plant.

### 3.5 Greenhouse Versus Open-field Cultivation

Greenhouse cultivation showed significant advantages over open-field cultivation (Table 2-5). Seedlings could be transplanted much earlier in the greenhouse. Transplanting in May in open-field is a standard practice in high mountain regions. The sub-zero temperature in April and May is not uncommon in the region; thus, early transplantation often results in frost damage. Due to early transplanting and more favorable temperatures inside the greenhouse, the growth and marketable yield of warm-season crops are significantly higher inside the greenhouse. The plant height of cucumber, capsicum, and brinjal inside the large greenhouse was 333.5 %, 104.3 %, and 187.6 %, respectively, higher at 90 DAT than in the open-field condition. A similar trend was observed in the number of leaves, stem diameter, and number of branches. However, the leaves of open-field-grown plants were thicker in all three crops than the greenhouse-grown plants. The results are consistent with the previous reports[4-5]. Thicker leaves under the open field may be due to lower temperatures.

Crops grown inside the large greenhouse resulted in the early harvest of cucumber, capsicum, and brinjal by 92, 82, and 75 days, respectively, compared to the open-field crops. Early crop harvest is a boon for the farmers as they can sell their produce early in the market. Cucumber yield inside the large greenhouse was recorded 2.1±0.1 kg as compared to 0.11±0.03 kg per plant in the open field. Similarly, greenhouse-grown capsicum and brinjal yields were recorded as 416.6 % and 414.3 % higher, respectively, than the open field.

## 4. CONCLUSION

Most farmers in Ladakh regions prefer low-cost, small-size (<35 feet in length) naturally ventilated passive solar greenhouses. However, the result of the present study suggested that a large greenhouse (60 feet in length, 24 feet in width) was better than a small greenhouse (32 feet in length, 18 feet in width) for growing warm-season crops in summer. The mean marketable yield of cucumber, capsicum, and brinjal was 112.1 %, 55.0 %, and 71.4 % higher inside the large greenhouse than in the small greenhouse. Hence, large, naturally ventilated greenhouses are suggested for high-altitude Ladakh regions for growing warm-season crops in summer.

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