

Improvement in productivity of strawberry (*Fragaria X ananassa* Duch.) under vertical farming system

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ABSTRACT

Vertical farming has evolved keeping in view the constraints of space due to the increasing population and shrinking agricultural land. Although vertical farming is more associated with small-duration crops, especially vegetables, flowers, and annuals such as strawberry can also be grown through the selection of appropriate variety and farming structure. An experiment was conducted to evaluate the effect of full spectrum light on the growth, flowering, fruiting, and yield of strawberry under a vertical farming system. Results revealed that plant height, plant spread, petiole length, number of leaves, number of fruits, average berry weight, and average yield were highest at light intensity of 175–200 $\mu\text{mol s}^{-1}\text{m}^{-2}$. It was observed that in T_1 when plants were at the fourth level or top level (L_4) of verticals under natural light, were superior in comparison to plants at lower levels in T_2 (L_3), T_3 (L_2), and T_4 (L_1) due to decreasing light intensity down to the base of verticals. The plants grown with an additional supply of artificial full spectrum light (AFSL) at these lower levels had performed better in T_5 (2 h at L_3), T_6 (4 h at L_2) and T_7 (6 h at L_1) in terms of growth, flowering, fruiting, and yield of strawberry and were at par to T_1 . In the vertical farming system, space, water, nutrient, and light optimization is possible as it ensures efficient resource utilization such as precision agriculture. Thus, the supply of AFSL is important to ensure sustainable yield in vertical farming.

1. INTRODUCTION

Strawberry is a major cash crop that is grown all over the world and is suitable for cultivation under a wide range of growing conditions including open fields, polyhouses, kitchen gardens, vertical farming, and hydroponics. The term “vertical farming” was first invented in 1915 by American geologist Gilbert Ellis Bailey which was primarily a sort of rooftop farming. However, in 1951 the concept of vertical farming changed to building towers of hydroponic units. The development of hydroponics and greenhouses had further expanded the concept of vertical farming; however, in 1991, Professor Dickson Despommier made an attempt to bring the food production units nearer to consumers as a way of decreasing carbon footprint. His constant efforts have resulted in the development of a blueprint of vertical farming and he is known as the founding father of modern vertical farming.

According to its size, layout, type of building, density, degree of control, and location, vertical farming is defined in a variety of ways [1]. The goal of vertical farming today is to use every square inch of space, whether in a city or a village, to grow as much food as possible

for the world's hungry people. The vertical farming system ensures a high degree of resource utilization efficiency which might be due to space optimization through the utilization of vertical space; water optimization through precision (drip) irrigation approach and closed-loop system; nutrient optimization through reduced nutrient runoff or leaching or fixation and through targeted delivery of nutrients; and light optimization through application of energy-efficient LED lighting which is major constraints of traditional farming system. Overall, vertical farming ensures a sustainable and resource-efficient model for precision or conservation and hi-tech agriculture. The framework of vertical farming has completely changed over the years. Today, it is a well-liked farming technique used all over the world. India is also seeing a rise in vertical farming. Due to the high net returns, vertical farming is attracting a lot of business interest. Vertical farming can be done on rooftops, balconies, buildings, and warehouses [2].

Building upward is another name for vertical farming, which is regarded as one of the most innovative agricultural technologies for minimizing the amount of land used [3]. According to Butturini and Marcelis [4], vertical gardening is the practice of growing plants on layers that are either vertically inclined or vertically stacked. This system aids in the production of foods that are stacked vertically. When this farming technique is applied, more crops can be grown in the same field [5]. In the United States and Canada, leafy greens (57%) are the most frequently planted crop, followed by tomatoes, flowers, and microgreens [6]. Using a vertical farming system, the cultivation area can be increased by 3–4 times, and a lot of healthy, high-quality fresh

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food can be produced all year [7]. The availability of resources that the crop can use such as water, nutrients, and lighting is significantly influenced by the plant spacing in vertical farming and is the impact reflected in the growth and yield of the plants [8].

The availability of solar radiation to each level of verticals is the major challenge in vertical farming. It has also been observed that very few research works have been done on growing strawberries under vertical farming using artificial light. A few researchers studied the impact of light on plant growth and a plant needs light for how much period for good vegetative growth and reproduction. There is limited information on the vegetative growth, flowering, fruiting, and yield parameters of strawberry under a vertical farming system. To fill this research gap and to generate knowledge regarding ideal growing conditions for strawberries under vertical farming systems using artificial light present investigation was planned.

2. MATERIALS AND METHODS

2.1. Experimental Area and Materials

2.1.1. Experimental site

The study was initiated in December at Agricultural Farm, School of Agriculture, Lovely Professional University, Phagwara, Punjab (India), during 2021–2023. The experimental area was located latitudinally around 31°14'41" N and longitudinally around 75°42'4" E at an altitude of 234 m from mean sea level in the Kapurthala district of Punjab region.

2.1.2. Varietal attributes

The well-established commercial cultivar, “Winter Dawn” was taken to carry out a study on the productivity of strawberry under a vertical farming system under outdoor conditions. This cultivar is well suited for the vertical farming system as the plant size is small (height-17 cm and spread 26 cm) with good yield (more than 500 g fruits per plant) so a high yield can be obtained at closer planting which is a key attribute for the vertical farming system. Further, it is resistant to *Colletotrichum* crown rot whereas moderately resistant to *Botrytis* and anthracnose fruit rot diseases.

2.2. Experimental Design and Details

2.2.1. Treatment details

The vertical structure consisted of four levels, namely, first layer (ground) (L_1), second layer (L_2), third layer (L_3), and fourth Layer (top) (L_4). The verticals were subjected to two light conditions, i.e., natural light (NL) and artificial full spectrum light (AFSL) of different durations. Different levels of verticals were subjected to an artificial supply of light for different time durations to meet out the requirement of minimum intensity of light at every level. The available light intensity was measured using a lux meter and the value was converted

in $\mu\text{mol s}^{-1}\text{m}^{-2}$ using 0.0185 as the calibration factor. The additional light duration for 0 h (D_0), 2 h (D_1), 4 h (D_2), and 6 h (D_3) was given to the strawberry plants. The treatment combinations, consisting of levels of verticals, nature of light provided, and duration of AFSL are depicted below:

2.2.2. Climate and growing media

In the Punjab region, only a few areas are suitable for the cultivation of strawberry because it is a subtropical area with humid and hot conditions. The optimum temperature recorded for the cultivation was 18–22°C. Punjab also receives monsoons from both southwest and northeast directions from August to February.

2.2.3. Vertical farming system

Strawberry was cultivated in the rack-type vertical system which was made of vertically stacked layers. It consists of an iron rack of 2 feet wide and 4 feet long having four levels fitted with an iron frame. Each level is 2 feet apart vertically and has grow bags of dimension 4 feet \times 2 feet (0.743 sqm). The AFSL of 22W (length 2 feet) was installed just below every level and provided to plants for different hours according to the needs of the plant. The light emitting diode (LED) (warm white and cool white diodes) grow tubes of 22W, replicating the sun's spectrum, were used as a source of AFSL which was emitting visible region of the spectrum (approximately 400–700 nm in wavelength). The schematic of the experimental setup is illustrated in Figure 1.

2.2.4. Agronomic practices

In the vertical system, the growing media was a composite mixture of sand, cocopeat, and vermicompost (3:2:1). The pH of the growing media was 6.4 with an electrical conductivity of 2.96 dSm⁻¹. Planting was done at a spacing of 20 cm \times 25 cm accommodating 15 plants in one rack. The fertilizer was applied through foliar application of N: P:K (21:21:21) at the rate 80:40:40 g per 0.743 sqm area at 15-day intervals. The water was provided through a drip connected with a water tank.

2.3. Observations Recorded

2.3.1. Plant growth parameters

The average plant height (cm), average number of leaves per plant, average petiole length (cm), and average plant spread (cm) were observed for each plant at 30, 60, and 90 days after planting. Plant height was taken from the collar region to the tip of the longest runner whereas plant spread was measured in East-West and North-South directions across the crown of the plant using a measuring scale. The leaves on each plant were counted manually and an average value was used for statistical analysis. The leaves of strawberry are borne along the crown on petioles (leafstalks) arranged in spiral fashion. The petiole length of each leaf on a plant was measured from the base at the crown to the point of connectivity of leaflets using a measuring scale

Treatments	Levels of verticals	Duration of AFSL	Available light intensity
T ₁	Fourth (Top) Level (L_4)	No AFSL (D_0)	208.37–209.96 $\mu\text{mol s}^{-1}\text{m}^{-2}$
T ₂	Third Level (L_3)	No AFSL (D_0)	175.15–178.55 $\mu\text{mol s}^{-1}\text{m}^{-2}$
T ₃	Second Level (L_2)	No AFSL (D_0)	158.66–160.37 $\mu\text{mol s}^{-1}\text{m}^{-2}$
T ₄	First (Bottom) Level (L_1)	No AFSL (D_0)	152.87–155.55 $\mu\text{mol s}^{-1}\text{m}^{-2}$
T ₅	Third Level (L_3)	2 h (D_1)	203.54–204.94 $\mu\text{mol s}^{-1}\text{m}^{-2}$
T ₆	Second Level (L_2)	4 h (D_2)	175.41–177.79 $\mu\text{mol s}^{-1}\text{m}^{-2}$
T ₇	First (Bottom) Level (L_1)	6 h (D_3)	159.12–160.95 $\mu\text{mol s}^{-1}\text{m}^{-2}$

*Since the experiment was under outdoor conditions all the treatments have received natural light.

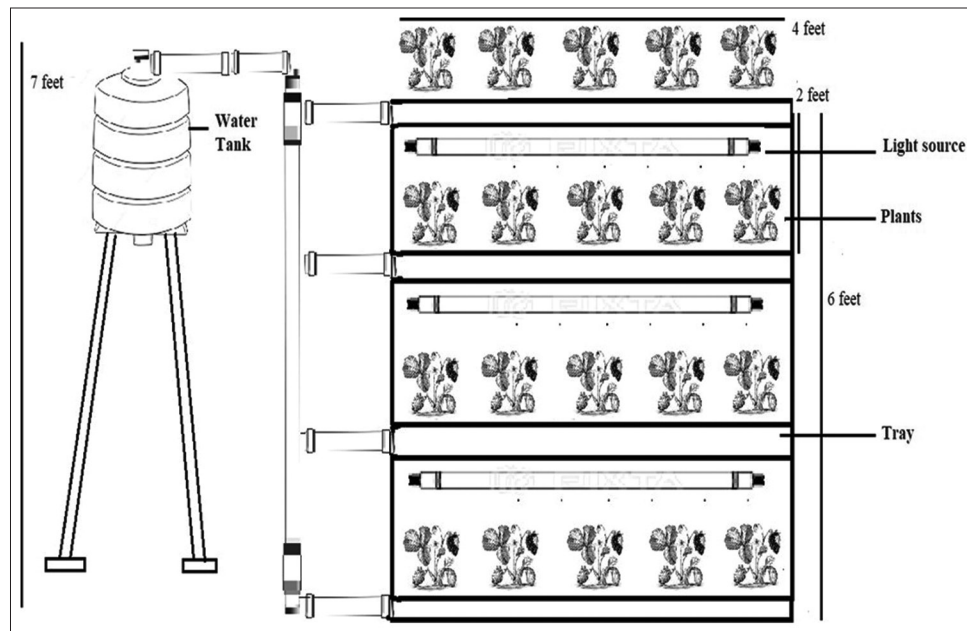


Figure 1: Schematic of the experimental setup.

and the mean was taken as the average petiole length per leaf.

2.3.2. Flowering and fruiting parameters

The number of days to bud formation, days to flowering (complete opening of flowers), and days to maturity were counted as a number of days from the date of planting. The floral buds and flowers present on each plant were counted after 20 days, 40 days, 55 days, 70 days, and 90 days of planting whereas the fruit count was done at the time of each harvesting and the total number of fruits per plant was estimated as the sum of each harvesting. The average number of buds, average number of flowers, and average number of fruits (berry) were estimated after dividing the total buds, flowers, and fruits count by the number of plants taken under observation in each replication. The fruit set percent was estimated using the formula given herewith.

$$\text{Fruit set (\%)} = \frac{\text{Average number of fruits harvested at maturity}}{\text{Average number of flowers count per plant}} \times 100$$

2.3.3. Yield and related parameters

Fruit harvesting was done manually at 5–6 days intervals. The weight of 10 randomly selected fruits from each plot was measured using electronic balance and the average berry weight was estimated and presented in grams (g). The fruit volume was measured in cc (cubic centimeter or mL) using a measuring cylinder. The total fruit weight of harvested fruits from all the plants was divided by a number of plants in treatment to observe the average yield of fruit (berry) in grams per plant. The average fruit weight per plant was used to calculate the fruit yield from 1000 sq. m. of vertical farming system using the given formula and the estimated yield was expressed in kg per 1000 sq.m. (there were 15 plants in the experimental area [0.743 sq.m.] of vertical rack).

$$\text{Yield (kg per 1000 sq.m.)} = \frac{\text{Average fruit yield per plant (g)} \times 15}{1000 (\text{g} \cdot \text{kg}^{-1}) \times 0.743 \text{ sq.m.}} \times 1000$$

2.4. Statistical Analysis

The data were statistically analyzed using MS Excel and OPSTAT software. The mean values of observations from three replications in each treatment were subjected to analysis for randomized complete block design to evaluate the statistical significance for variation due to treatments as explained by Gomez and Gomez [9]. The recorded mean of all the quantitative traits for each replication was exposed to statistical analysis for testing the significance of variation among different levels of verticals and the light duration by F-test [10].

3. RESULTS AND DISCUSSION

3.1. Average Plant Height of Strawberry

The observations recorded for average plant height [Table 1] were significantly affected by levels of vertical structure and the duration of AFSL. The plants at the top or fourth level (T_4) have grown better in the absence of AFSL; however, the average height of plants at lower levels was at par when subjected with AFSL in T_3 , T_6 and T_7 . At 90 days of planting, the highest plant height (20.17 ± 0.455 cm and 19.98 ± 0.26 cm) was observed with a maximum duration of AFSL in T_6 (4 h at L_2) and T_7 (6 h at L_1), respectively, which were 1.25 and 1.32 times (T_3 and T_4 , respectively) higher than the plants grown at the same level under the availability of NL only. Strawberry plants grown under full spectrum light demonstrated noticeable improvements in their growth compared to those subjected to NL conditions only. The optimized light spectrum provided by full spectrum LEDs facilitated photosynthesis and stimulated overall plant development, resulting in increased height and a wider plant spread [11]. The light-induced nutrient uptake depends on fluctuating light quality which is sensed by the photoreceptors of the plants [12] and is enhanced due to the development of a photosynthetic sink for nutrients in leaves [13]. Uddin *et al.* [14] in their study revealed that LED lights increased the plant height which is somehow similar to our study.

The plant height is the function of a balance between apical dominance and axillary bud initiation. Blue light is actively involved in the improvement of callusing and the number of axillary buds but has

Table 1: Average plant height (cm) of strawberry plants grown at different levels of verticals under different treatments.

Treatments	At 30 days after planting			At 60 days after planting			At 90 days after planting		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T ₁	13.19±0.274 ^a	13.82±0.069 ^{ab}	13.50±0.153 ^{ab}	22.81±0.37 ^a	23.49±0.468 ^a	23.15±0.41 ^a	17.67±0.285 ^b	17.97±0.384 ^{bc}	17.82±0.33 ^b
T ₂	13.09±0.197 ^a	14.25±0.191 ^a	13.67±0.134 ^a	18.37±0.154 ^c	19.48±0.183 ^c	18.93±0.168 ^c	14.55±0.222 ^d	15.67±0.285 ^c	15.11±0.251 ^c
T ₃	11.72±0.117 ^b	12.8±0.029 ^c	12.26±0.054 ^c	17.43±0.439 ^d	18.89±0.254 ^{cd}	18.16±0.342 ^{cd}	15.62±0.09 ^c	16.73±0.019 ^c	16.18±0.037 ^c
T ₄	12.05±0.047 ^b	13.03±0.388 ^c	12.54±0.204 ^c	17.09±0.044 ^{de}	18.33±0.094 ^d	17.71±0.046 ^d	14.70±0.234 ^{cd}	15.57±0.11 ^c	15.13±0.169 ^c
T ₅	13.14±0.266 ^a	13.58±0.2 ^b	13.36±0.074 ^{ab}	21.59±0.167 ^b	21.12±0.164 ^b	21.36±0.164 ^b	18.10±0.522 ^b	18.26±0.784 ^b	18.18±0.604 ^b
T ₆	13.03±0.174 ^a	13.43±0.137 ^{bc}	13.23±0.149 ^b	17.39±0.041 ^{de}	18.52±0.358 ^d	17.95±0.166 ^d	19.19±0.205 ^a	21.16±0.707 ^a	20.17±0.455 ^a
T ₇	12.81±0.337 ^a	14.12±0.02 ^a	13.46±0.175 ^{ab}	16.61±0.221 ^c	18.20±0.081 ^d	17.40±0.071 ^d	19.49±0.205 ^a	20.47±0.318 ^a	19.98±0.26 ^a
SE (m) ±	0.23	0.16	0.12	0.26	0.28	0.25	0.30	0.46	0.36
CD (at 0.05)	0.71	0.49	0.38	0.79	0.85	0.77	0.91	1.42	1.12
CV%	3.12	2.04	1.64	2.36	2.43	2.25	3.01	4.46	3.60

All values are mean±SEM values of three replications, T₁: Fourth (top) level with only natural light (without artificial full spectrum light), T₂: Third level with only natural light, T₃: Second level with only natural light, T₄: First (bottom) level with only natural light, T₅: Third level with artificial full spectrum light (AFSL) of 2 h, T₆: Second level with AFSL of 4 h, T₇: First (bottom) level with artificial full spectrum light (AFSL) of 6 h. The mean values with different superscript letters in a column are significantly different (p<0.05).

an inhibitory action on the sprouting of vegetative buds leading to increased apical dominance whereas red light reduces the apical dominance which reflects an antagonistic model of regulation stem branching and growth in the presence of red and blue lights mediated by photoreceptors [15]. A contrasting mechanism explained by Muleo *et al.* [16] indicated the inhibition of internodal elongation and enhanced axillary bud formation under blue light as a photon fluence rate-dependent mechanism instead of phytochrome-regulated. The red light alone may result in low photosynthetic capacity, low maximum quantum yield of chlorophyll fluorescence, low photosynthetic capacity and unresponsive stomatal conductance [17,18], excessive stem elongation, and leaf disorders [19] the so-called Red-Light Syndrome. In this case, blue light plays an active role to counteract the excessive effect of red light and alleviates “red light syndrome” to assure good plant development [17].

The various studies on the influence of red and blue light on organogenesis confirm a species-dependent mechanism. Nhut *et al.* [20] reported irregular plantlet growth in *Fragaria x ananassa* due to excessive and prolonged red light availability whereas plantlet growth was inhibited under a monochromatic supply of blue light. Jao *et al.* [21] also reported a shorter stem of plants and a higher chlorophyll content under RL-BL application which highlights the requirement of full spectrum light for regulation of both plant height and chlorophyll biosynthesis. However, the AFSL provided to the strawberry plants in the current study has a broad spectrum composition of white light enriched in the most useful wavelengths (blue light, red light, and green light) which could play an important role in the vertical farming system [22].

3.2. Average Number of Leaves per Plant

The observations recorded for an average number of leaves per plant [Table 2] were significantly affected by treatments given at all days of observations (30, 60, and 90 days after planting). The average number of leaves per plant was highest at lower levels of verticals when subjected with additional full spectrum light in T₆ (4 h at L₂) and T₇ (6 h at L₁) followed by T₅ (2 h at L₃) and were at par to T₁ when plants were at top level (L₄) without additional supply of light. Somewhat similar results were observed in the study of Uddin *et al.* [14] which showed an increased number of leaves with the effect of LED lights. A greater fraction of red light is responsible for the impaired development of leaves, i.e., long petioles and thin wide leaves with

reduced chlorophyll content, resembling to shade avoidance response under low light; however, the presence of blue light in AFSL could be accountable to counteract the red-light effect to ensure healthy development leaves under vertical farming system [6]. Although a greater fraction of blue light is also associated with abnormalities in leaf development and results in sun-type leaves (high leaf thickness with reduced leaf area) which is antagonized by green light [6]. The AFSL provided to strawberry plants in the present study includes all these spectra (red light, blue light, and green light) which might be responsible for the proliferation of leaf primordia and the development of healthy leaves. Moreover, full spectrum LEDs encouraged the initiation and expansion of leaves, thereby increasing the available leaf area for efficient photosynthesis [23].

3.3. Average Length of Petioles

The observations recorded for average petiole length [Table 3] were significantly affected by the level of verticals and additional hours of AFSL at all days of observations (30, 60, and 90 days after planting). The plants grown with the addition of full spectrum light at first, second, and third levels had greater average lengths of petiole when supplied with additional hours of AFSL as in T₆ (4 h at L₂) and T₇ (6 h at L₁) followed by T₅ (2 h at L₃) and the results were at par to T₁ when plants were at the top level (L₄) without additional supply of light. The longer petioles in the plants exposed to full spectrum light could be attributed to enhanced nutrient absorption and transport within the plants [24]. This supply of nutrients from roots is in coordination with photosynthetic activities in shoots through signaling molecules such as phytohormones, proteins, and sucrose and is probably linked to ion uptake [25]. Nhut *et al.* [20] reported elongated petioles in *Fragaria x ananassa* under red light; however, the leaves turned yellowish green with irregular *in vitro* growth which might be resolved by adding the blue light to the spectrum as advocated by Miao *et al.* [17]. The application of AFSL in the present study did not reflect such abnormalities which could be attributed to the presence of a broad spectrum of light including red light, blue light, and green light.

3.4. Average Spread of Strawberry Plants

The levels of verticals and the duration of artificial light significantly affected the plant spread [Table 4] on all observation days (30, 60, and 90 days after planting). Under NL supply, the plants have a wider spread at the fourth (top) level (L₄) of verticals and were better in comparison

Table 2: Average number of leaves of strawberry plants grown at different levels of verticals under different treatments.

Treatments	At 30 days after planting			At 60 days after planting			At 90 days after planting		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T ₁	10.67±0.57 ^b	15.93±0.176 ^{ab}	13.30±0.351 ^{ab}	14.47±0.176 ^b	19.40±0.757 ^a	16.93±0.448 ^a	17.20±0.231 ^b	17.00±1.206 ^a	17.10±0.603 ^{ab}
T ₂	10.67±0.24 ^b	13.27±0.751 ^b	11.97±0.371 ^b	11.73±0.067 ^c	15.13±0.593 ^{bc}	13.43±0.328 ^c	14.60±0.231 ^d	13.47±1.954 ^b	14.03±0.949 ^c
T ₃	12.87±0.521 ^a	13.53±1.267 ^b	13.20±0.723 ^{ab}	13.47±0.176 ^{bc}	13.20±0.2 ^c	13.33±0.176 ^c	15.73±0.533 ^c	12.13±0.706 ^b	13.93±0.481 ^c
T ₄	10.87±0.371 ^b	10.67±0.176 ^b	10.77±0.12 ^b	10.80±0.503 ^c	13.87±0.24 ^c	12.33±0.338 ^c	13.27±0.176 ^c	13.73±0.57 ^b	13.50±0.305 ^c
T ₅	12.93±0.467 ^a	16.53±1.235 ^a	14.73±0.835 ^a	14.27±0.57 ^b	15.93±0.353 ^b	15.10±0.458 ^b	17.13±0.24 ^b	15.80±0.416 ^{ab}	16.47±0.088 ^b
T ₆	12.87±0.067 ^a	13.80±1.514 ^{ab}	13.33±0.788 ^{ab}	16.80±0.416 ^a	13.87±0.819 ^c	15.33±0.437 ^b	19.80±0.116 ^a	16.60±0.346 ^{ab}	18.20±0.115 ^a
T ₇	11.93±0.267 ^{ab}	14.47±0.968 ^{ab}	13.20±0.569 ^{ab}	16.53±1.434 ^a	14.13±0.176 ^c	15.33±0.736 ^b	19.27±0.291 ^a	12.60±0.503 ^b	15.93±0.291 ^b
SE (m) ±	0.39	0.99	0.59	0.61	0.55	0.45	0.29	0.96	0.49
CD (at 0.05)	1.22	3.05	1.82	1.88	1.69	1.38	0.89	2.95	1.49
CV%	5.78	12.23	7.89	7.53	6.30	5.34	3.00	11.44	5.39

All values are mean±SEM values of three replications, T₁: Fourth (top) level with only natural light (without artificial full spectrum light), T₂: Third level with only natural light, T₃: Second level with only natural light, T₄: First (bottom) level with only natural light, T₅: Third level with artificial full spectrum light (AFSL) of 2 h, T₆: Second level with AFSL of 4 h, T₇: First (bottom) level with artificial full spectrum light (AFSL) of 6 h. The mean values with different superscript letters in a column are significantly different (p<0.05).

Table 3: Average petiole length (cm) of strawberry plants grown at different levels of verticals under different treatments.

Treatments	At 30 days after planting			At 60 days after planting			At 90 days after planting		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T ₁	12.96±0.255 ^a	12.57±0.215 ^{ab}	12.77±0.22 ^a	22.33±0.347 ^a	17.73±0.384 ^b	20.03±0.205 ^a	17.27±0.262 ^b	13.25±0.685 ^b	15.26±0.356 ^{cd}
T ₂	12.83±0.207 ^a	13.30±0.38 ^a	13.06±0.183 ^a	18.11±0.184 ^c	15.34±0.305 ^{cd}	16.72±0.245 ^c	14.27±0.224 ^d	15.31±0.773 ^{ab}	14.79±0.276 ^d
T ₃	11.45±0.122 ^b	11.95±0.055 ^b	11.70±0.038 ^b	17.15±0.406 ^d	16.25±0.129 ^c	16.70±0.157 ^c	15.23±0.082 ^c	14.25±0.387 ^b	14.74±0.191 ^d
T ₄	11.81±0.013 ^b	11.87±0.532 ^b	11.84±0.265 ^b	16.85±0.047 ^d	15.23±0.122 ^d	16.04±0.054 ^c	14.41±0.262 ^{cd}	14.83±0.325 ^{ab}	14.62±0.28 ^d
T ₅	12.84±0.295 ^a	12.85±0.177 ^{ab}	12.84±0.072 ^a	21.33±0.184 ^b	17.93±0.765 ^b	19.63±0.408 ^{ab}	17.70±0.472 ^b	13.85±0.218 ^b	15.78±0.262 ^c
T ₆	12.71±0.188 ^a	12.69±0.347 ^{ab}	12.70±0.191 ^a	17.07±0.041 ^d	20.85±0.697 ^a	18.96±0.334 ^b	18.87±0.175 ^a	16.08±0.262 ^a	17.47±0.212 ^a
T ₇	12.53±0.33 ^{ab}	13.27±0.312 ^a	12.90±0.303 ^a	16.30±0.219 ^d	20.17±0.299 ^a	18.24±0.117 ^b	19.13±0.238 ^a	14.07±0.349 ^b	16.60±0.278 ^b
SE (m) ±	0.24	0.30	0.19	0.25	0.32	0.25	0.28	0.47	0.26
CD (at 0.05)	0.73	0.91	0.57	0.78	0.99	0.76	0.87	1.44	0.81
CV%	3.28	4.07	2.58	2.38	2.87	2.36	2.93	4.58	2.93

All values are mean±SEM values of three replications, T₁: Fourth (top) level with only natural light (without artificial full spectrum light), T₂: Third level with only natural light, T₃: Second level with only natural light, T₄: First (bottom) level with only natural light, T₅: Third level with artificial full spectrum light (AFSL) of 2 h, T₆: Second level with AFSL of 4 h, T₇: First (bottom) level with artificial full spectrum light (AFSL) of 6 h. The mean values with different superscript letters in a column are significantly different (p<0.05).

to lower levels (T₂, T₃, and T₄). However, when additional full spectrum light was given to strawberry plants grown at lower levels (the first, second, and third levels) of vertical structure, the plant spread was improved. Under supplementary AFSL for 6 h, 4 h, and 2 h in T₇, T₆, and T₅, respectively, the plant spread (E-W and N-S) in strawberry was at par to the T₁ and was 1.11, 1.10, and 1.23 times greater than the plant spread in T₄, T₃, and T₂, respectively. The application of AFSL in vertical farming resulted in plants' better growth of side branches and overall plant spread.

AFSLs consist of visible spectra predominantly consisting of blue light, green light, and red light. The red light stimulates the photosynthetic apparatus and phytochromes [26] which regulates the photosynthesis and biomass accumulation [27] whereas the blue component of LED light effectively stimulates phytochromes as well as cryptochromes and phototropins [26] which regulates photomorphogenesis, stomatal movement, biosynthesis of chlorophyll, and anthocyanin as well as biomass accumulation [27]. The presence of green light components in AFSL regulates leaf expansion, stem stretching, and stomatal conductance which could have played a significant role in the plant spread of strawberry. Thus, the simultaneous presence of blue and red light in AFSL compensated for their mutual effects on biomass

production and a positive growth response [28,29]. The present finding implies that the improved light spectrum played a role in optimizing the physical structure of strawberry plants, potentially resulting in higher crop production and biomass accumulation [30]. The dependence of plant spread on light intensity at different levels of verticals could be associated with alteration in water use efficiency and stomatal conductance of strawberry plants [31] or the activation of phytochrome by different light duration resulting in regulation of activities of transcription factors [32]. Alteration of light environment can bring change in morphogenesis which could be associated with auxin homeostasis as it plays a crucial role in regulation of plant growth and development. Further, light stimulates auxin transport to roots resulting in light-induced elongation of primary roots for efficient nutrient uptake [33].

3.5. Flowering Parameter Analysis

The number of days required for bud formation and flower initiation was smaller with a greater number of flowers per plant at the top level of verticals (T₁) due to the availability of sufficient light intensity [Table 5]. However, the delay in bud initiation and flowering with lesser flower count was noticed in strawberry plants at lower levels

Table 4: Average plant spread (cm) of strawberry plants grown at different levels of verticals under different treatments.

Treatments	At 30 days after planting			At 60 days after planting			At 90 days after planting		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
East-West direction									
T ₁	7.06±0.512 ^{ab}	8.21±0.097 ^a	7.63±0.294 ^a	15.19±0.098 ^b	17.32±0.311 ^a	16.26±0.189 ^b	16.83±0.274 ^a	20.99±0.635 ^a	18.91±0.293 ^a
T ₂	6.83±0.394 ^b	8.26±0.326 ^a	7.55±0.191 ^a	11.53±0.478 ^d	13.31±0.911 ^b	12.42±0.307 ^c	11.85±0.344 ^d	17.91±0.268 ^b	14.88±0.161 ^d
T ₃	7.17±0.474 ^{ab}	7.63±0.294 ^{ab}	7.40±0.365 ^a	12.93±0.408 ^c	13.87±0.291 ^b	13.40±0.081 ^d	13.52±0.261 ^c	17.31±1.1 ^b	15.41±0.507 ^d
T ₄	5.60±0.3 ^b	6.75±0.074 ^b	6.18±0.149 ^b	12.45±0.326 ^{cd}	13.30±0.503 ^b	12.88±0.182 ^{de}	12.42±0.25 ^d	17.20±0.27 ^b	14.81±0.255 ^d
T ₅	6.15±0.308 ^b	8.07±0.294 ^{ab}	7.11±0.299 ^a	14.89±0.358 ^b	18.01±0.396 ^a	16.45±0.11 ^{ab}	16.38±0.372 ^{ab}	19.14±0.269 ^{ab}	17.76±0.095 ^b
T ₆	6.75±0.314 ^b	7.39±0.299 ^b	7.07±0.198 ^{ab}	17.68±0.405 ^a	16.83±0.667 ^a	17.25±0.428 ^a	15.11±0.14 ^b	18.25±0.375 ^b	16.68±0.213 ^c
T ₇	8.13±0.415 ^a	7.04±0.266 ^b	7.58±0.327 ^a	14.26±0.31 ^b	14.41±0.701 ^b	14.33±0.402 ^c	15.70±0.099 ^b	17.75±1.373 ^b	16.72±0.638 ^{bc}
SE (m) ±	0.41	0.25	0.28	0.37	0.61	0.29	0.28	0.64	0.34
CD(at 0.05)	1.26	0.79	0.88	1.15	1.88	0.89	0.87	1.97	1.05
CV%	10.36	5.79	6.84	4.56	6.92	3.41	3.37	6.00	3.57
North-South direction									
T ₁	7.42±0.332 ^a	6.45±0.255 ^b	6.94±0.287 ^b	13.27±0.301 ^{bc}	15.62±0.338 ^{ab}	14.44±0.131 ^b	11.21±0.318 ^b	22.22±1.084 ^a	16.71±0.54 ^a
T ₂	7.38±0.07 ^a	4.53±0.185 ^d	5.95±0.099 ^{cd}	11.51±0.221 ^d	11.34±1.046 ^c	11.42±0.536 ^c	11.14±0.397 ^b	16.51±0.166 ^b	13.82±0.281 ^b
T ₃	5.69±0.171 ^{bc}	5.38±0.07 ^c	5.54±0.088 ^d	12.07±0.341 ^{cd}	10.68±0.175 ^c	11.38±0.09 ^c	8.79±0.376 ^c	16.57±1.587 ^b	12.68±0.85 ^b
T ₄	5.17±0.128 ^c	6.81±0.013 ^{ab}	5.99±0.07 ^{cd}	12.93±0.445 ^c	11.06±0.671 ^c	12.00±0.531 ^c	9.34±0.262 ^c	16.06±1.25 ^b	12.70±0.521 ^b
T ₅	8.00±0.342 ^a	7.35±0.374 ^a	7.68±0.029 ^a	14.27±0.358 ^b	16.93±0.229 ^a	15.60±0.215 ^{ab}	13.15±0.467 ^a	21.67±0.453 ^a	17.41±0.457 ^a
T ₆	5.95±0.357 ^{bc}	6.39±0.135 ^b	6.17±0.149 ^c	16.62±0.428 ^a	15.59±0.682 ^{ab}	16.11±0.497 ^a	12.18±0.456 ^{ab}	16.01±0.096 ^b	14.10±0.274 ^b
T ₇	6.18±0.501 ^b	4.59±0.243 ^d	5.38±0.244 ^d	14.28±0.42 ^b	14.75±0.631 ^b	14.52±0.226 ^b	10.71±0.297 ^{bc}	16.93±0.54 ^b	13.82±0.254 ^b
SE (m) ±	0.29	0.22	0.17	0.36	0.63	0.39	0.40	0.86	0.47
CD(at 0.05)	0.90	0.69	0.51	1.12	1.95	1.20	1.24	2.65	1.46
CV%	7.72	6.55	4.63	4.62	8.00	4.93	6.39	8.29	5.68

All values are mean±SEM values of three replications, T₁: Fourth (top) level with only natural light (without artificial full spectrum light), T₂: Third level with only natural light, T₃: Second level with only natural light, T₄: First (bottom) level with only natural light, T₅: Third level with artificial full spectrum light (AFSL) of 2 h, T₆: Second level with AFSL of 4 h, T₇: First (bottom) level with artificial full spectrum light (AFSL) of 6 h. The mean values with different superscript letters in a column are significantly different (p<0.05).

(T₂, T₃, and T₄) of vertical structure which could be due to a reduction in the intensity of NL. When additional full spectrum light was given, the plants that were grown at the lower levels (T₅, T₆, and T₇), namely, first, second, and third levels had improved performance in terms of earliness in flowering as well as the number of flowers per plant. They also performed at par to the fourth level in NL conditions (T₁) for early bud formation which confirms the essentiality of AFSL for flower induction at lower levels of vertical structure.

The control activity of light through AFSL under short days (winter months) solar radiation enhances the crop growth and development efficiency by optimizing the photosynthetic activities which results in changes in internal rhythms to bring morphological and reproductive changes such as flower bud differentiation or improve the biosynthesis and accumulation of plant metabolites necessary for defense against biotic and abiotic stresses [34]. The optimized light spectrum provided by full spectrum LEDs likely played a role in expediting physiological processes and initiating earlier bud development. In addition, the time required for bud formation to reach maturity was accelerated, resulting in faster fruit ripening and shorter maturation periods [35,36]. Longer durations of full spectrum light exposure, particularly during the flowering stage, can promote bud formation and potentially reduce the time it takes for buds to develop as flowers. Providing sufficient light during the appropriate growth stages is crucial for optimal bud development and flower production [37,38]. Extended exposure to full spectrum light to promote flower induction and increase the number of flowers is a time-dependent process and is influenced by multiple

components of the daylight spectrum; however, for harnessing the full advantage of the application of LEDs in crop production it is necessary to know the diurnal impact of light quality on the whole process from floral evocation to anthesis including the involvement of photoreceptors and the flowering regulatory genes [39].

3.6. Fruiting of Strawberry

The various fruiting and yield-related parameters, namely, fruit count per plant, days to fruit maturity, fruit volume, and average berry weight were significantly influenced by levels of verticals and the duration of AFSL provided at different levels. The number of fruits per plant [Table 6] and fruit set percentage [Figure 2] was significantly reduced down to the levels in verticals from T₁ to T₄ due to reduced availability of light. However, the fruit count and fruit set were improved in the treatments with an additional supply of AFSL at lower levels of vertical structure where the highest fruit set and fruit count was noticed at T₅ (L₃ + AFSL for 2 h), T₆ (L₂ + AFSL for 4 h), and T₇ (L₁ + AFSL for 6 h) which were at par to T₁ (L₄ + only NL) in comparison to T₂ (L₃ + only NL), T₃ (L₂ + only NL), and T₄ (L₁ + only NL). The plants exposed to only NL matured earlier when plants were at the fourth level (T₁) and were superior in comparison to T₂, T₃, and T₄; however, the supply of additional duration of AFSL has not hastened the fruit maturity [Table 6]. The fruit volume and average berry weight [Table 6] of strawberry were greater in T₁, i.e., plants grown at the top level of verticals under NL conditions. The fruit volume was further reduced down the levels

Table 5: Flowering parameters of strawberry plants grown at different levels of verticals under different treatments.

Treatments	Days to bud formation			Number of buds per plant		
	2022	2023	Pooled	2022	2023	Pooled
T ₁	60.83±0.167 ^b	61.33±0.167 ^{ab}	61.08±0.084 ^{ab}	23.00±0.764 ^b	25.56±0.483 ^{ab}	24.28±0.576 ^b
T ₂	61.67±0.166 ^{ab}	60.83±0.167 ^b	61.25±0.144 ^{ab}	23.17±0.928 ^b	25.56±0.588 ^{ab}	24.36±0.459 ^b
T ₃	62.17±0.166 ^a	60.83±0.441 ^b	61.50±0.289 ^a	24.83±0.928 ^{ab}	24.44±0.678 ^b	24.64±0.266 ^b
T ₄	61.67±0.441 ^{ab}	61.33±0.167 ^{ab}	61.50±0.289 ^a	22.50±0.001 ^b	25.00±0.768 ^b	23.75±0.387 ^b
T ₅	61.50±0.5 ^{ab}	60.17±0.441 ^b	60.83±0.167 ^b	25.33±0.726 ^a	26.78±0.447 ^a	26.06±0.556 ^a
T ₆	61.33±0.167 ^{ab}	61.67±0.441 ^a	61.50±0.25 ^a	25.83±0.167 ^a	23.89±0.618 ^b	24.86±0.266 ^{ab}
T ₇	61.33±0.167 ^{ab}	60.67±0.601 ^b	61.00±0.289 ^{ab}	26.67±0.167 ^a	23.89±0.22 ^b	25.28±0.102 ^{ab}
SE (m) ±	0.30	0.27	0.17	0.64	0.57	0.41
CD (at 0.05)	0.92	0.83	0.52	1.97	1.76	1.26
CV%	0.84	0.77	0.48	4.53	3.95	2.87

Treatments	Days to flowering			Number of flowers per plant		
	2022	2023	Pooled	2022	2023	Pooled
T ₁	65.50±0.001 ^b	64.67±0.441 ^b	65.08±0.22 ^b	23.11±0.222 ^a	24.00±0.333 ^{ab}	23.56±0.241 ^{ab}
T ₂	65.83±0.166 ^b	65.83±0.333 ^{ab}	65.83±0.082 ^b	22.67±0.333 ^{ab}	24.44±0.678 ^{ab}	23.56±0.199 ^{ab}
T ₃	66.00±0.289 ^b	66.00±0.289 ^{ab}	66.00±0.001 ^b	23.33±0.667 ^a	22.44±0.948 ^b	22.89±0.388 ^{ab}
T ₄	67.00±0.289 ^a	66.17±0.167 ^a	66.58±0.22 ^a	21.78±0.676 ^b	23.78±0.675 ^b	22.78±0.675 ^b
T ₅	66.67±0.167 ^{ab}	65.17±0.334 ^b	65.92±0.221 ^b	22.00±0.333 ^b	25.67±0.193 ^a	23.83±0.095 ^a
T ₆	67.00±0.5 ^a	65.50±0.289 ^{ab}	66.25±0.382 ^{ab}	21.22±0.484 ^b	22.56±0.483 ^b	21.89±0.443 ^b
T ₇	66.50±0.289 ^{ab}	66.17±0.441 ^a	66.33±0.082 ^{ab}	21.89±0.401 ^b	22.33±0.333 ^b	22.11±0.339 ^b
SE (m) ±	0.26	0.32	0.16	0.30	0.58	0.33
CD (at 0.05)	0.80	0.99	0.50	0.93	1.77	1.01
CV%	0.67	0.84	0.43	2.35	4.23	2.46

All values are mean±SEM values of three replications, T₁: Fourth (top) level with only natural light (without artificial full spectrum light), T₂: Third level with only natural light, T₃: Second level with only natural light, T₄: First (bottom) level with only natural light, T₅: Third level with artificial full spectrum light (AFSL) of 2 h, T₆: Second level with AFSL of 4 h, T₇: First (bottom) level with artificial full spectrum light (AFSL) of 6 h. The mean values with different superscript letters in a column are significantly different (p<0.05).

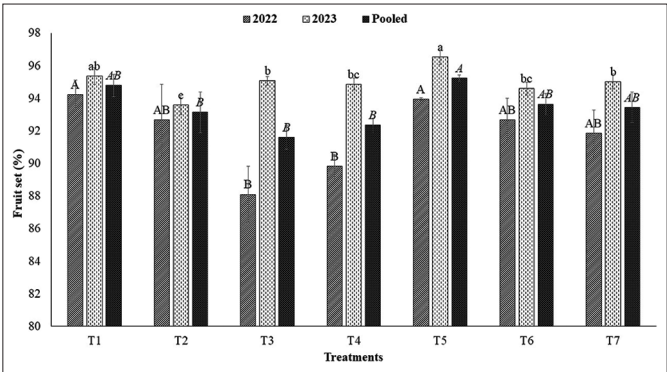


Figure 2: Fruit set (%) of strawberry plants grown at different levels of verticals under different treatments.

of verticals (L₄ to L₁) due to the reduced intensity of NL. However, when additional duration of AFSL was provided at lower levels, the fruit volume was significantly increased at T₅ (L₃ + AFSL for 2 h), T₆ (L₂ + AFSL for 4 h), and T₇ (L₁ + AFSL for 6 h) in comparison to T₂ (L₃ + only NL), T₃ (L₂ + only NL), and T₄ (L₁ + only NL).

Full spectrum light, which encompasses the necessary wavelengths for both photosynthesis and reproductive development, is essential for a successful fruit set in strawberries. Adequate light intensity and quality during the flowering stage positively impact pollination, fertilization, and subsequent fruit formation [40]. The improved light spectrum likely stimulated floral initiation and promoted greater

flower production [41], leading to enhanced pollination efficiency and fruit set, ultimately resulting in higher fruit yield [42]. Optimal light quality and intensity are influential factors in determining fruit size and volume. Studies indicate that optimizing the light spectrum and intensity can contribute to increased fruit volume in strawberries cultivated under different levels of verticals [43].

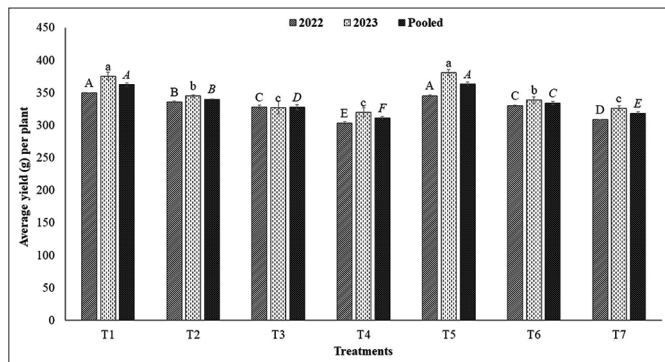
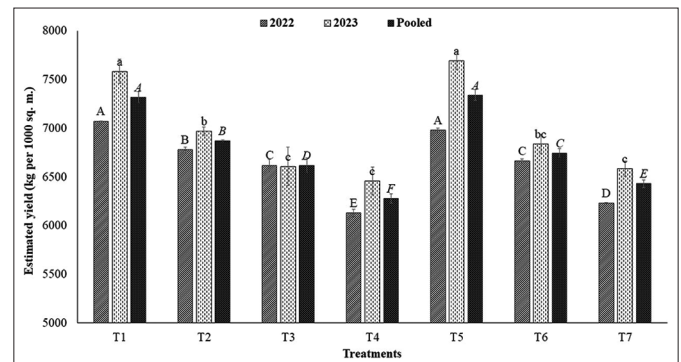
3.7. Yield Attributes of Strawberry

It was observed that average fruit yield per plant [Figure 3] and estimated fruit yield (kg per 1000 sq.m.) [Figure 4] were significantly varied at different levels of verticals under NL as well as additional duration of AFSL. The average fruit yield per plant of strawberry was greater in T₁, i.e., plants grown at the top level of verticals under NL conditions were further reduced down the levels of verticals (L₄ to L₁) due to reduced intensity of NL. However, when additional duration of AFSL was provided at lower levels, the average fruit yield per plant was significantly increased at T₅ (L₃ + AFSL for 2 h), T₆ (L₂ + AFSL for 4 h), and T₇ (L₁ + AFSL for 6 h) in comparison to T₂ (L₃ + only NL), T₃ (L₂ + only NL), and T₄ (L₁ + only NL). A similar trend was noticed for the estimated yield (kg per 1000 sq.m.) of strawberry under natural and supplementary doses of light. The correlation study of average light intensity available to the plants under different treatments with the various parameters [Figure 5] also confirms a strong and positive correlation with the fruit set (0.889**), average berry weight (0.820*), and yield of strawberry (0.976**) which confirms that the higher yield under T₅, T₆, and T₇ could be associated to high available light intensity due to AFSL provided at the lower levels in these treatments. An

Table 6: Fruiting parameters of strawberry grown at different levels of verticals under different treatments.

Treatments	Days to fruit maturity			Number of fruits per plant		
	2022	2023	Pooled	2022	2023	Pooled
T ₁	72.50±0.289 ^c	72.33±0.333 ^b	72.42±0.301 ^c	21.78±0.40 ^a	22.89±0.402 ^b	22.33±0.384 ^{ab}
T ₂	73.50±0.5 ^c	73.33±0.441 ^b	73.42±0.363 ^d	21.00±0.51 ^{ab}	22.89±0.776 ^b	21.94±0.474 ^{ab}
T ₃	72.83±0.441 ^c	74.50±0.001 ^a	73.67±0.221 ^{cd}	21.89±0.89 ^a	21.33±0.839 ^{bc}	21.61±0.39 ^b
T ₄	75.50±0.5 ^{ab}	73.83±0.166 ^{ab}	74.67±0.167 ^b	19.56±0.48 ^c	22.56±0.588 ^{bc}	21.06±0.529 ^{bc}
T ₅	74.67±0.441 ^b	73.33±0.333 ^b	74.00±0.144 ^c	20.67±0.33 ^b	24.78±0.294 ^a	22.72±0.11 ^a
T ₆	75.00±0.289 ^{ab}	73.83±0.667 ^{ab}	74.42±0.221 ^{bc}	19.67±0.51 ^{bc}	21.33±0.384 ^{bc}	20.50±0.441 ^c
T ₇	76.00±0.289 ^a	74.83±0.166 ^a	75.42±0.221 ^a	20.11±0.62 ^{bc}	21.22±0.294 ^c	20.67±0.419 ^{bc}
SE (m) ±	0.34	0.36	0.17	0.34	0.53	0.30
CD (at 0.05)	1.06	1.10	0.54	1.05	1.64	0.93
CV%	0.80	0.84	0.41	2.86	4.10	2.42
Treatments	Fruit volume (cc)			Average berry weight (g)		
	2022	2023	Pooled	2022	2023	Pooled
T ₁	14.00±0.157 ^a	14.24±0.255 ^a	14.12±0.144 ^a	16.10±0.297 ^{ab}	16.43±0.536 ^a	16.26±0.388 ^{ab}
T ₂	14.07±0.285 ^a	13.64±0.179 ^{ab}	13.86±0.058 ^a	16.01±0.365 ^b	15.12±0.597 ^b	15.57±0.336 ^b
T ₃	12.74±0.204 ^b	13.57±0.125 ^b	13.16±0.039 ^b	15.02±0.542 ^c	15.35±0.227 ^{ab}	15.19±0.329 ^b
T ₄	12.88±0.369 ^b	12.83±0.119 ^c	12.86±0.204 ^b	15.54±0.297 ^{bc}	14.21±0.609 ^b	14.88±0.449 ^b
T ₅	14.40±0.051 ^a	13.89±0.123 ^{ab}	14.14±0.045 ^a	16.74±0.287 ^{ab}	15.38±0.064 ^{ab}	16.06±0.126 ^{ab}
T ₆	13.90±0.285 ^a	13.74±0.4 ^{ab}	13.82±0.082 ^a	16.80±0.424 ^a	15.88±0.165 ^{ab}	16.34±0.28 ^a
T ₇	12.91±0.371 ^b	12.94±0.172 ^{bc}	12.93±0.211 ^b	15.37±0.467 ^{bc}	15.37±0.298 ^{ab}	15.37±0.381 ^b
SE (m) ±	0.28	0.21	0.13	0.24	0.39	0.24
CD (at 0.05)	0.88	0.66	0.41	0.73	1.21	0.73
CV%	3.63	2.72	1.68	2.58	4.40	2.61

All values are mean±SEM values of three replications, T₁: Fourth (top) level with only natural light (without artificial full spectrum light), T₂: Third level with only natural light, T₃: Second level with only natural light, T₄: First (bottom) level with only natural light, T₅: Third level with artificial full spectrum light (AFSL) of 2 h, T₆: Second level with AFSL of 4 h, T₇: First (bottom) level with artificial full spectrum light (AFSL) of 6 h. The mean values with different superscript letters in a column are significantly different (p<0.05).

**Figure 3:** Average yield (g/plant) of strawberry grown at different levels of verticals under different treatments.**Figure 4:** Estimated yield (kg per 1000 sq.m.) of strawberry grown at different levels of verticals under different treatments.

increase in the yield of strawberry plants was observed in a somewhat similar study by Hanenberg *et al.* [44] and Hidaka *et al.* [45]. The weight of strawberries is influenced by multiple factors, such as genetic traits, nutrient availability, and environmental conditions. Full spectrum light has the potential to enhance photosynthesis and overall plant vitality, which could result in larger berry sizes [46]. -Full spectrum light, provided by technologies such as full spectrum LEDs, can optimize plant growth and development, potentially leading to increased yields in vertical farming systems. Research has demonstrated the beneficial impact of full spectrum light on plant yield in various crops including strawberries under greenhouse [47,48].

4. CONCLUSION

In the current study, the strawberry plants have resulted in the highest productivity when grown at the top level (L₄) in the vertical farming system. At lower levels of the verticals, the additional supply of AFSL for a certain duration is essential to ensure greater plant height, number of leaves per plant, petiole length, plant spread, number of flowers per plant, number of fruits per plant, fruit set percentage, fruit size, average berry weight, and fruit yield of strawberry. The additional duration of AFSL resulted in higher average fruit yield per plant at lower levels, namely, T₅ (L₃ + AFSL for 2 h), T₆ (L₂ + AFSL

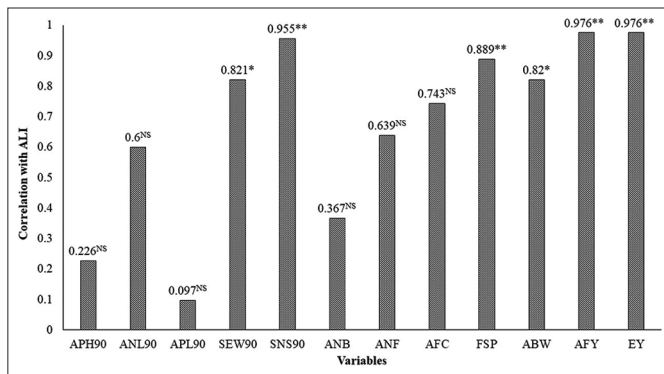


Figure 5: Correlation between available light intensity through natural and artificial full spectrum light and various growth and yield parameters.

for 4 h), and T_7 (L_1 + AFSL for 6 h) and was at par to T_1 (top level of vertical + only NL) under outdoor cultivation of strawberry. Thus, under a vertical farming system, it is advised to provide an additional supply of light to maintain the available light intensity as high as $200 \mu\text{mol s}^{-1}\text{m}^{-2}$ which seems to be a typical light intensity required for strawberry.

4.1. Potential Benefits of Vertical Farming System

The present study confirms that vertical farming of strawberry ensures optimization of various resources, namely, space, light, water, and nutrients so it embraces promising implications for future agriculture practices as it holds potential scope to solve the expected challenges of land availability, water scarcity and health issue of abiotic and biotic communities including human and soil. Thus, it can ensure increased food production in urban areas to enhance food security by reducing reliance on the traditional system of agriculture for a consistent supply of food. Further, its potential to reduce environmental impact may contribute to sustainable and resilient agricultural practices, offering a viable solution for the evolving challenges of global food production.

4.2. Potential Limitations of Present Study

One of the major challenges of the vertical farming system is the high initial investment cost for infrastructure which can be resolved through low-cost establishment as per the design given in the present study. Energy consumption as AFSL is a question of its sustainability which can be resolved after adding solar panels as an energy source. Further, it is investigated for a limited number of crops so there is a further need of investigation by including diverse group of crops. Further, the impact of different spectra of light is species-dependent and is based on a complex molecular mechanism that needs to be further explored. The waste generated through this experiment such as using nutrient solution is a matter of concern. These limitations need to be addressed through ongoing research as it is posing a potential obstacle to its scalability and sustainability.

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6. AUTHORS' CONTRIBUTION

All authors made significant contributions to the design of the research work, data collection, data analysis, and interpretation.

They have also contributed to the draft of the present manuscript and have revised it critically to improve the concept. All are in agreement for submission of this manuscript to the current journal, have approved this for publication, and bear accountability for all aspects of this work. All the authors are eligible to be authors as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

7. FUNDING

There is no funding to report.

8. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

9. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

10. DATA AVAILABILITY

The data are available with the first and corresponding author as it is from the dissertation work of the first author. It will be made available on request.

11. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declares that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

12. PUBLISHER'S NOTE

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