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RESEARCH ARTICLE

Vertical farming: A potential farming practice for lettuce production

Suwimon Wicharuck[1], Nuttapon Khongdee[2], Tasanee Pripanakul[3], Niwooti Whangchai[4], Tipsukhon Pimpimol[4], and Chatchawan Chaichana[1*]

[1]Chiang Mai University, Faculty of Engineering, Energy Technology for Environment Research Center, Chiang Mai, Thailand.
[2]Chiang Mai University, Faculty of Agriculture, Department of Highland Agriculture and Natural Resources, Chiang Mai, Thailand.
[3]Chiang Mai University, Faculty of Agriculture, Department of Plant and Soil Science, Chiang Mai, Thailand.
[4]Maejo University, Faculty of Fisheries Technology and Aquatic Resources, Chiang Mai, Thailand.
[*]Corresponding author (c.chaichana@eng.cmu.ac.th).

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ABSTRACT

Land for agriculture is becoming limited in urban areas and the concept of vertical farming could help increase land productivity. Therefore, this study was conducted to investigate the potential of vertical farming on sunlight availability for lettuce (*Lactuca sativa* L.) production in the greenhouse system. The experimental design was completely randomized design with two different farming systems: Horizontal and vertical farming systems. Ten planting shelves including five horizontal shelves (HS) and five vertical shelves (VS) with three vertical levels as upper (VS_U), middle (VS_M) and lower (VS_L) were constructed. Two lettuce varieties, 'Green Oak' (*L. sativa* var. *crispa*) and 'Green Cos' (*L. sativa* var. *longifolia*), were selected for comparative measurement. Lettuce was planted in both HS and VS systems. Photosynthetically photon flux density (PPFD) was continuously monitored throughout lettuce growing period. Lettuce height and canopy width were measured weekly. Leaf fresh weight (FW) and dry weight (DW) were also evaluated. The averaged PPFD values were 245, 217, 158 and 147 μmol m^{-2} s^{-1} for HS, VS_U, VS_M and VS_L, respectively. Higher values of height and canopy width were observed on HS in comparison to VS. Values of FW and DW on HS were significantly higher as compared to VS. In addition, higher plant growth occurred from upper to lower levels on VS while lower FW and DW were observed from top to bottom. Plant densities of VS (24 plant m^{-2}) were 1.5 times higher than HS (16 plant m^{-2}). Light use efficiency was also pointed out that VS (0.46 g mol^{-1}) tended to have better values in comparison to HS (0.28 g mol^{-1}).

Key words: *Lactuca sativa*, lettuce production, light intensity, vertical farming.

INTRODUCTION

Rapid urbanization, natural disasters, global warming, and uncontrolled use of chemicals and pesticides have a negative impact on soil fertility. In addition, soil productivity has decreased dramatically, soil fertility has diminished, and the amount of land available to each individual has decreased (Lehman et al., 2015; Mir et al., 2022). Greenhouse agriculture is gaining popularity in order to alleviate environmental constraints and boost land productivity to satisfy future food demands (FAO, 2017). Therefore, a new practice known as "vertical farming" (VF) has been developed and is well-known nowadays.

Vertical farming is a system to cultivate crops in a limited area by growing crops into the vertical aspect with several growing container levels as in staking arrangement. The VF can increase yield per unit area when compared to the horizontal farming system or conventional cultivation (Tyson et al., 2001; Touliatos et al., 2016; Resh, 2022). In general, the VF is operated in an indoor closed system under a controlled environment and used the LEDs for the lighting source (Kozai et al., 2019; Pennisi et al., 2019; Avgoustaki and Xydis, 2020; Wittmann et al., 2020).

Light in terms of quality, quantity, direction and period is the main environmental parameter for plant energy (Devlin et al., 2007; Khongdee et al., 2021; Paradiso and Proietti, 2022). These parameters strongly affect the development and morphology of plants, including regulating plant behavior during the photosynthetic process. Light wavelength between 400 and 700 nm is defined as photosynthetically active radiation (PAR) and it is the light spectrum portion used by plants for photosynthesis (Carruthers et al., 2001). Photosynthetically photon flux density (PPFD) can be identified as the photon flux density of PAR per unit area and time which can be defined in a unit of μmol m^{-2} s^{-1} (Carruthers et al., 2001). The PPFD can be converted to daily light integral (DLI). The DLI is the cumulative PAR amounts obtained by crops daily and it is a result of light intensity and duration (Gao et al., 2020).

Optimal ranges of PPFD and DLI are varied according to different crop varieties. For example, lettuces and herbs prefer the values of PPFD 100-300 μmol m^{-2} s^{-1} and DLI 12-17 mol m^{-2} d^{-1} (Kozai et al., 2019; Pennisi et al., 2019). Recommended DLI for strawberries are 20 mol m^{-2} d^{-1} for strawberry propagation improvement (Zheng et al., 2019). The choice of crops which can be grown in indoor farming must be rapid growth and high retail prices. Therefore, leafy vegetables like lettuces and herbs are commonly selected for planting in indoor VF systems due to fast-growing and high market needs and prices (Larsen et al., 2020) including less energy use per crop cycle as well.

Crop yield is directly related to the light intensity because light intensity increased plant soluble sugars and resulted in part of DM (Larsen et al., 2020). Marcelis et al. (2005) pointed out that a 1% increase in light intensity, a higher yield by 0.25%-1.50% can be observed. However, the increase in light intensity does not always improve yields. Moreover, the values of DLI over 16.5 mol m^{-2} d^{-1} gave no further increases in total fresh weight in sweet basil (Dou et al., 2018).

Under natural sunlight, a reduction of light intensity (PPFD values) in VF occurred from the upper to lower levels of the shelves, causing inadequate light for the photosynthetic process (carbohydrate accumulation). As pointed out by Touliatos et al. (2016) that upper to lower gradients in intensity of light and shoot fresh weight inhibit plant growth in indoor and greenhouse vertical columns. However, the vertical shelves (VS) produced more crops harvested per unit area of growing space than the horizontal shelves (HS). Compared to conventional cultivation, VS results in yield increases from 129% to 200% and enhanced revenues of 3.6 to 5.5 USD m^{-2} (Liu et al., 2004). Top to bottom gradients in light intensity and shoot fresh weight inhibit plant growth in both indoor and greenhouse vertical columns (Touliatos et al., 2016).

The best term to measure the overall performance of VF would be the harvested fresh yields per unit of emitted light by the light supply (Jin et al., 2021). The light use efficiency (LUE) of a crop can be defined by the incident light for growth efficiently used by plants which is estimated by the ratio of plant dry weight to the overall amounts of light that plants obtained during the growing cycle (Legendre and van Iersel, 2021). Furthermore, irrigation water according to crop evapotranspiration can improve crop production in limited water areas and it can optimize the use of water to maximize the crop yields.

Many studies have been conducted on growing lettuce in indoor hydroponically vertical farming in the closed system using LEDs for the lighting system. However, there is still lacking information on how the influence of sunlight intensity on vertical compared to horizontal shelves. Therefore, this study aimed at investigating the effect of vertical farming on sunlight availability for lettuce growth and yield performance under horizontal and vertical shelves planted in the greenhouse without supplementing artificial light.

MATERIALS AND METHODS

Study site and planting systems

The study was conducted in a 10.0 m × 20.0 m greenhouse at Hang Dong district, Chiang Mai province, Thailand, with average air temperature of about 22-30 °C and relative humidity of 66.2%-85.4%. The greenhouse was separated into two sections (10.0 m in width, 10.0 m in length and 2.8 m in height). The side of the greenhouse was opened and the roof was covered by the 0.15 mm thick transparent plastic. Two different planting systems were prepared as vertical and horizontal shelves (Figure 1). Five A frame-shaped of vertical shelves (VS) were placed 0.8 m apart from each other and the VS were triangle-shaped, with dimensions of 1.0 m width, 1.5 m height and 7.5 m length. Each VS is comprised of three levels: upper, middle and lower levels with 0.4 m apart. The upper, middle and lower levels were 1.2, 0.8 and 0.4 m in height, respectively. The VS contained six plant trays of 0.2 m width × 0.2 m height × 7.5 m length. White plastic mulch (density of 110 g m^{-2}) was used to prepare a growing media container along the planting tray and underneath covered with the 0.15 mm thick transparent plastic.

Five horizontal shelves (HS) were prepared. The size of the HS was 1.0 m width × 7.5 m length and 1.0 m height, with 0.8 m distance from each other. Roof-tiles were placed as a base and covered by transparent plastic (0.15 mm); then, a blue net was to be used for plant containers. The HS was set to be as a control for this study.

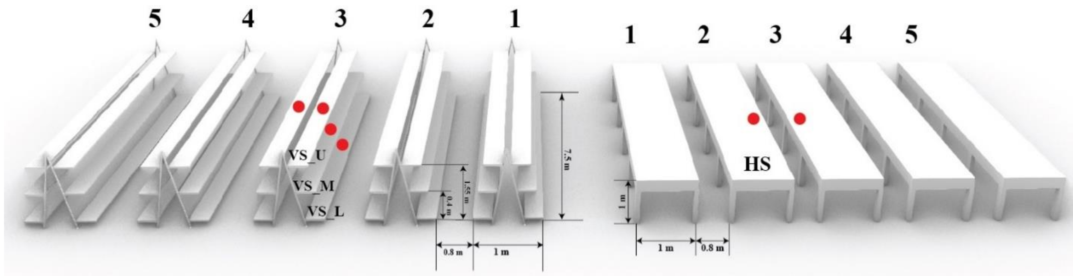

Figure 1. Vertical and horizontal shelves arrangement. HS: Horizontal shelves; VS: vertical shelves; VS_U: vertical shelves at the upper level; VS_M: vertical shelves at the middle level; and VS_L: vertical shelves at lower levels. The number between 1 and 5 are shelve numbers. Red dots are the position of installed light sensors.

Growing media and irrigation schedule

Growing media comprised of surface soil (developed by the Faculty of Agriculture, Chiang Mai University, Chiang Mai, Thailand), rice husk, rice husk ash, coconut husk and chicken manure with the ratio of 2:1:1:1:1, adding 50 g charcoal and rock phosphate. The composition was well mixed and samples were taken for properties analysis at the Department of Plant and Soil Science, Faculty of Agriculture, Chiang Mai University, Chiang Mai, Thailand (Table 1). Packing of the growing media into the plant trays was done according to the dry bulk density (g cm^{-3}). The weight of growing media for VS was 405 kg (67.5 kg for each plant tray) and 450 kg for one HS.

Irrigation water (IW; cm^3 $plant^{-1}$ d^{-1}) was calculated from crop consumptive use or crop evapotranspiration using the following equation:

$$IW = ETc = ETo \times Kc$$

Where ETc is actual crop evapotranspiration (mm d^{-1}) and it was calculated according to the Allen et al. (1998). The ETc was estimated using reference crop evapotranspiration (ETo; mm d^{-1}) and crop coefficient (Kc). The ETo was determined from the Penman-Monteith equation and the Kc was taken from the FAO (Allen et al., 1998). Drip tape irrigation was installed in the middle of planting pots, with the rate of 2 L h^{-1} from the emitter. The automatic timer was used and the total IW volume was 150 cm^3 $plant^{-1}$ d^{-1}.

Table 1. Physical and chemical properties of growing media.

Properties	Standard method	Values
Dry bulk density, g cm^{-3}	Core method	0.42
Moisture (by volume), $\%cm^3\ cm^{-3}$	Gravimetric method	20.90
pH	pH meter	6.79
Organic matter, %	Walkley & Black	11.30
Available P, %	Vanadomolybdate	0.54
Exchangeable K, %	Atomic emission spectrometry (AES)	0.22

Lettuce cultivation

Surface of growing media was covered by white plastic mulch and planting pits were prepared with the diameter of 90 mm. Spacing between plants were 0.25 m. One VS contained 144 pots (6 plant trays × 24 pots) and one HS comprised of 96 pots (4 planting lines × 24 pots). Lettuces (*Lactuca sativa* L.) as 'Green Oak' (*L. sativa* L. var. *crispa* L.) and 'Green Cos' (*L. sativa* L. var. *longifolia* Lam.), were transplanted on both VS and HS after 14 d of seedling.

Data collection

Height and canopy width were measured every 7 d after transplanting (DAT) using a vernier caliper. 'Green Oak' (GO) and 'Green Cos' (GC) were selected for a comparative variety. 'Green Oak' and 'Green Cos' were harvested at maturity (approximately 30 DAT) and fresh weight (FW) was then recorded. After that, the samples were dried at 65 °C for 3 d and weighed to calculate the dried weight (DW). The photosynthetically photon flux density (PPFD) was recorded every 30 min using the WatchDog LightScout Quantum light sensor (Spectrum Technologies, Aurora, Illinois, USA). The photosynthetically active radiation (PAR) light sensors were placed on both VS and HS. The positions of the PAR light sensors were at the HS2/HS3 (2 sensors) and the VS3 (6 sensors: 2 sensors on the upper level, 2 sensors on the middle level and 2 sensors on the lower levels for both left- and right-side). One PAR light sensor was installed outside the greenhouse. Then, daily light integral (DLI) was calculated as DLI (mol m^{-2} d^{-1}) = PPFD (µmol m^{-2} s^{-1}) × day length (h) × 0.0036.

Statistical analysis

The experiment was designed as a completely randomized design with two treatments (HS and VS) and five replicates. The analysis was calculated for each type of lettuce. Differences of means of yield were performed for both VS and HS using the Student's t-test and the differences of levels on VS were analyzed by one-way ANOVA, followed by post hoc Turkey's honestly significant difference (HSD) test. Growth on the 28 DAT was compared using one-way ANOVA and the means were compared by Tukey's HSD. Furthermore, linear regressions were calculated for the relationships between growth and cumulative DLI.

RESULTS

Variations of PPFD and DLI values inside and outside greenhouse

Sunlight intensity both outside and inside the greenhouse was measured as PPFD (µmol m^{-2} s^{-1}); then, calculated DLI was obtained from PPFD and photoperiods. The measured PPFD was generally observed from 06:00 to 18:00 h during the measurement period, with the highest peak between 11:00 and 15:00 h (Figure 2a). The photoperiods of sunlight were 10-13 h d^{-1}, approximately. Average daily values of PPFD and DLI showed the same trends (Figures 2b, 2c). The highest values of PPFD and DLI were found outside the greenhouse in comparison to inside the greenhouse. Horizontal shelves received the higher PPFD and DLI values as compared to VS. When compared among the values on the VS, a reduction of light intensity occurred from the upper to the lower levels. The highest PPFD and DLI were found under VS_H while VS_L had the lowest PPFD and DLI values. In addition, the calculated DLI values inside the greenhouse (HS = 10.4 mol m^{-2} d^{-1}, VS_H = 9.1 mol m^{-2} d^{-1}, VS_M = 6.5 mol m^{-2} d^{-1} and VS_L = 5.9 mol m^{-2} d^{-1}) were lower when compared to the average DLI values outside the greenhouse (35.7 mol m^{-2} d^{-1}) as seen in Figure 2d. This caused in low sunlight received by the lettuces on VS during the day than HS as values of 1.2, 1.6 and 1.8 times under VS_U, VS_M and VS_L, respectively.

Lettuce growth and yields on horizontal and vertical farming system

Table 2 shows mean values of height and canopy width of GO and GC under horizontal and vertical farming systems. Means of lettuce height growing on HS (GO = 155.0 mm and GC = 263.5 mm) were significantly higher than those on VS (GO at U = 105.6 mm, M = 98.8 mm and L = 111.3 mm and GC at U = 190.0 mm), with the exception on GC at VS_M as 244 mm and VS_L as 267.5 mm. Effect of VS-L on GC had the highest values of height as compared to the others. Comparison of height at the different vertical levels of the VS, height tended to increase from upper to lower level. Highly significant differences of canopy width between lettuces planting on HS (GO = 353.0 mm and GC = 340.9 mm) and VS at different vertical levels were observed for both GO and GC. Moreover, nonsignificant differences of canopy width occurred on different vertical levels of VS. Canopy width of GO under VS had slightly different values among different vertical levels of 277.8 mm at the upper level, 283.8 mm at the middle level, and 273.1 mm at the lower level, while GC had greater values (U = 265.0 mm, M = 279.0 mm, and L = 276.9 mm). A high standard deviation under VS was observed for both lettuce varieties due to high variations of plants. Some plants were too small and did not grow well during the first week after lettuce transplanting.

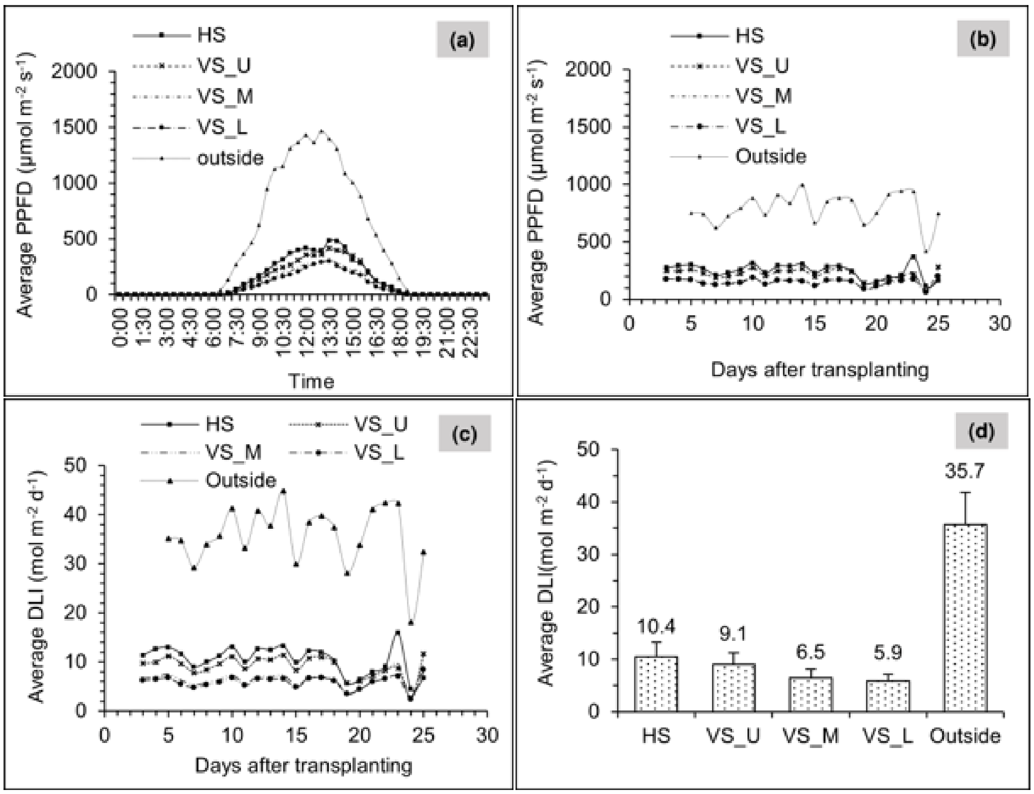

Figure 2. Typical daily photosynthetically photon flux density (PPFD) (a), average daily PPFD (b), average daily light integral (DLI) (c) and mean average DLI (d) for light intensity of both outside and inside the greenhouse. The error bars corresponded to the standard deviation. HS: Horizontal shelves; VS_U: vertical shelves at the upper level; VS_M: vertical shelves at the middle level; VS_L: vertical shelves at the lower level.

Variations of height and canopy width showed the same trends during the measurement periods (Figure 3). The average values of height and canopy width increased with times on both GO and GC. Slightly differences of height were found on HS and VS (Figure 3). Horizontal shelves of GO and GC tended to have the highest height while VS_L and VS_M had the lowest. Among different vertical levels of VS, the height tended to increase from lower to upper level. In addition, the average values of plant canopy width were higher on HS in comparison to the VS (Figure 3c, 3d). Lower values of plant canopy width occurred under VS_U for both GO and GC.

Table 2 shows that the average fresh weight (FW) and dry weight (DW) of GO and GC under HS and VS during the measurement periods. The average FW of two different lettuces was higher on HS with the average values of 124.6 g plant^{-1} for GO and 137.6 g plant^{-1} on GC in comparison to VS on different vertical levels (GO_VS_U = 67.4 g plant^{-1}, GO_VS_M = 42.6 g plant^{-1}, GO_VS_L = 58.9 g plant^{-1}, GC_VS_U = 51.9 g plant^{-1}, GC_VS_M = 83.5 g plant^{-1} and GC_VS_L = 77.9 g plant^{-1}).

Table 2. Mean average values and standard deviations (SD) of plant growth (height and canopy width) and yield under horizontal and vertical shelves recorded at 28 d after transplanting. *Significant difference at 95% of confidential level; ns: nonsignificant difference at 95% of confidential level. HS: Horizontal shelves; VS: vertical shelves; t-value: independent sample t-test; GO: 'Green Oak'; GC: 'Green Cos'; N: number of investigation samples; HS: horizontal shelves; VS: vertical shelves; U: vertical shelves at the upper level; M: vertical shelves at the middle level; L: vertical shelves at the lower level. Different letters on VS indicate significant differences of means among levels at $p < 0.05$ regarding to the Turkey HSD's test.

Parameters	Types	HS	VS		t-Value	P-Value
Plant growth						
Height, mm	GO	155.0 ± 9.5	U (N = 9)	105.6 ± 18.8a	9.5	0.000*
Mean ± SD		(N = 20)	M (N = 8)	98.8 ± 27.5a	5.7	0.001*
			L (N = 8)	111.3 ± 41.9a	4.5	0.000*
			Mean	105.2 ± 29.6		
	GC	263.5 ± 28.5	U (N = 10)	190.0 ± 46.4a	4.5	0.001*
		(N = 17)	M (N = 10)	244.0 ± 56.0b	1.0	ns
			L (N = 8)	267.5 ± 38.5b	-0.3	ns
			Mean	231.4 ± 56.8		
Canopy width, mm	GO	353.0 ± 28.3	U (N = 9)	277.8 ± 27.3a	6.7	0.000*
Mean ± SD		(N = 20)	M (N = 8)	283.8 ± 37.7a	5.3	0.000*
			L (N = 8)	273.1 ± 41.1a	5.0	0.001*
			Mean	278.2 ± 34.3		
	GC	340.9 ± 29.4	U (N = 10)	265.0 ± 29.3a	6.5	0.000*
		(N = 17)	M (N = 10)	279.0 ± 34.5a	5.0	0.000*
			L (N = 8)	276.9 ± 23.9a	5.4	0.000*
			Mean	273.4 ± 29.5		
Yield						
Leave fresh weight, g plant^{-1}	GO	124.6 ± 37.8	U (N = 9)	67.4 ± 30.1a	4.0	0.000*
Mean ± SD		(N = 20)	M (N = 8)	42.6 ± 44.3a	4.9	0.000*
			L (N = 8)	58.9 ± 49.9a	3.8	0.000*
			Mean	56.7 ± 41.4		
	GC	137.6 ± 35.1	U (N = 10)	51.9 ± 35.2a	6.3	0.000*
		(N = 17)	M (N = 10)	83.5 ± 46.5a	3.6	0.000*
			L (N = 8)	77.9 ± 45.1a	3.9	0.000*
			Mean	68.8 ± 42.3		
Leave dry weight, g	GO	5.4 ± 1.3	U (N = 9)	4.8 ± 2.0a	0.9	ns
Mean ± SD		(N = 20)	M (N = 8)	3.2 ± 2.3a	2.6	0.03*
			L (N = 8)	3.1 ± 2.3a	3.4	0.002*
			Mean	3.7 ± 2.2		
	GC	5.6 ± 1.4	U (N = 10)	5.0 ± 2.5a	0.9	ns
		(N = 17)	M (N = 10)	4.7 ± 2.2a	1.2	ns
			L (N = 8)	3.6 ± 2.0a	2.8	0.001*
			Mean	4.5 ± 2.3		

Relationship between growth and cumulative DLI

Figures 4 and 5 show the relationships between cumulative DLI and plant growth (height and canopy width) of GO and GC on HS and VS during the measurement periods. The cumulative DLI were calculated as sum of daily DLI over the crop cycle of 25 d. The values of cumulative DLI were varied for HS (259 mol m^{-2}) and VS at different levels (U = 209 mol m^{-2}, M = 149 mol m^{-2} and L = 145 mol m^{-2}). The results indicate that there were significant positive relationships between cumulative DLI and plant growth under different farming systems at $P < 0.01$. The determination of coefficient (R^2) was varied according to different shelves positions and lettuce varieties. The GO, R^2 values between height and cumulative DLI were 0.77 in HS, 0.72 in VS_U, 0.69 in VS_M and 0.51 in VS_L while the relationships between canopy width and cumulative DLI had the R^2 of 0.88, 0.64, 0.51 and 0.61 in HS, VS_U, VS_M and VS_L, respectively. On the GC, the R^2 values between growth (height and canopy width) and cumulative DLI ranged as height *vs*. DLI at HS = 0.88, VS_U = 0.64, VS_M = 0.51 and VS_L = 0.61 and as canopy width *vs*. DLI of 0.85, 0.67, 0.63 and 0.77 in HS, VS_U, VS_M and VS_L, respectively. These relationships indicated that an increase in cumulative DLI tended to improve the plant morphology in terms of height and canopy width for GO and GC growing on both HS and VS.

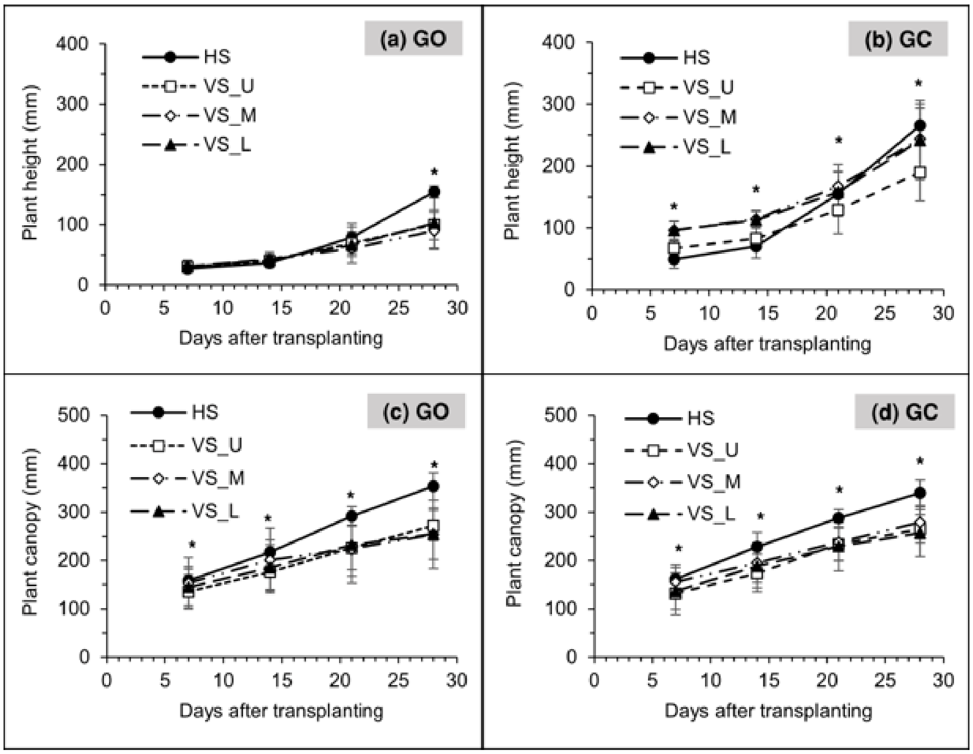

Figure 3. Variations of height and canopy width after transplanting under horizontal and vertical farming systems. Data points indicated the mean and error bars corresponded to the standard deviation. *Significant differences of means at 95% of confidential level. GO: 'Green Oak'; GC: 'Green Cos'; HS: horizontal shelves; VS_U: vertical shelves at the upper level; VS_M: vertical shelves at the middle level; VS_L: vertical shelves at the lower level.

Table 3. Summary of resource use in the experiment under horizontal and vertical farming systems. Plant density was 16 plant m^{-2} in HS and 24 plant m^{-2} in VS at the spacing of 0.25 between plants. HS: Horizontal shelves; VS: vertical shelves; FW: leaf fresh weight; DW: leaf dry weight.

Parameters	HS	VS	VS/HS
Fresh yield, g m^{-2}	1993	1500	0.7
Dry yield, g m^{-2}	88	97	1.1
Water use efficiency (WUE)			
WUE calculated as the ratio of FW to total IW, g m^{-2} mm^{-1}	0.73	0.35	0.5
WUE calculated as the ratio of DW to total IW, g m^{-2} mm^{-1}	0.031	0.023	0.7
Light use efficiency (LUE)			
Ratio of FW to total daily light integral (DLI), g mol^{-1}	6.7	7.3	1.1
Ratio of DW to total DLI, g mol^{-1}	0.28	0.46	1.6

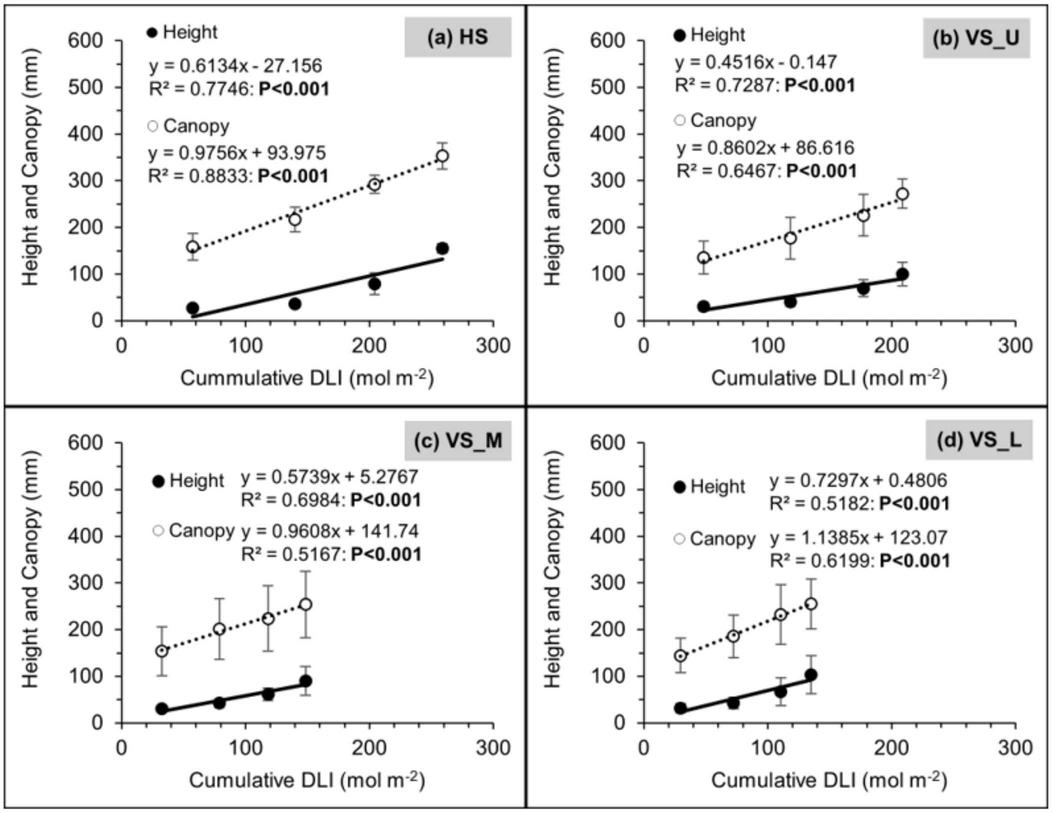

Figure 4. Relationships between lettuce 'Green Oak' (GO) growth and cumulative daily light integral (DLI) at four measurement times (at 7, 14, 21 and 28 d after transplanting). HS: Horizontal shelves; VS: vertical shelves; VS_U: vertical shelves at the upper level; VS_M: vertical shelves at the middle level; VS_L: vertical shelves at the lower level. Data points indicated means and error bars corresponded to the standard deviation.

DISCUSSION

Plant growth and yields are greatly influenced by environmental factors such as temperature, relative humidity and light (Kozai et al., 2019; SharathKumar et al., 2020). For vertical farming, photosynthetic reaction is directly affected by light in terms of intensity and duration (Chen et al., 2004; Zhang et al., 2018) because plants need optimum light amounts for growing. Moreover, light can improve the photosynthetic process and stimulate the plant to accumulate carbohydrate and sugar which is resulted in plant biomass. In this study, lettuces height and canopy width on HS were higher than those values on VS at different vertical levels leading to significantly lower yields under VS compared to HS. Lower the leaves fresh weight (FW) and dry weight (DW) was also observed from upper to lower levels, with the exception of GC. This correlated to the study of Touliatos et al. (2016) who pointed out that lettuce yields on HS were greater than VS and the yields on the VS were lower from top to bottom. Significant differences in FW and DW between HS and VS at the upper level were observed. On the VS, there were nonsignificant differences in FW and DW among different levels for both lettuce varieties (Table 2). In addition, height and canopy width on VS tended to increase from lower to upper levels. This was due to low PPFD and DLI on VS at the middle and lower levels as seen in Figure 2, which resulted in the ineffective development of lettuces causing plant cell to develop longer than usual. The plant growth depends on the process of photosynthesis which is generally improved by the increase in light intensity (Fu et al., 2012; Kang et al., 2013). Under the same PPFD, the biomass of lettuce exposed to longer photoperiod was found to be higher because longer photoperiod allows for more carbohydrates to accumulate in the plant cells (Zhang et al., 2018). Unlike the other studies conducted under artificial light using LEDs, this study was conducted under natural sunlight. The photoperiods were the same around 10-13 h d^{-1} for HS and VS at the same time but the PPFD values were varied according to different shelves and levels. This was associated to the studies of Fu et al. (2012) that romaine lettuce growing under 400 and 200 µmol m^{-2} s^{-1} showed no differences in fresh weight.

In addition, the resource use efficiency was taken into account in order to compare a potential of VS to the HS for cultivation. Resource use efficiency in agriculture can be explained as the concept of maximizing output by using less land, water and energy (Haque, 2006). Therefore, the main three factors are concerned in this study comprising of plant numbers occupied per unit area (plant m^{-2}), water use efficiency (g m^{-2} mm^{-1}) and light use efficiency (LUE, g mol^{-1}). The VS can produce more crops at the same unit area in comparison to HS because plants can be cultivated by expanding vertical columns into upright positions (Eigenbrod and Gruda, 2015). Plant density at the same spacing between plants (0.25 m) on VS was 1.5 times higher than HS as values of 24 plant m^{-2} on VS and 16 plant m^{-2} on HS in the study. This was correlated to the investigation of Touliatos et al. (2016) that crop productivity was estimated as yields per unit floor area; yields on VS were 13.8 times more than on the HS. However, it also depends on the characteristics of the crops, for example, wire crops like grapes and fruit trees are not suitable for vertical farming systems because these plants need more vertical space.

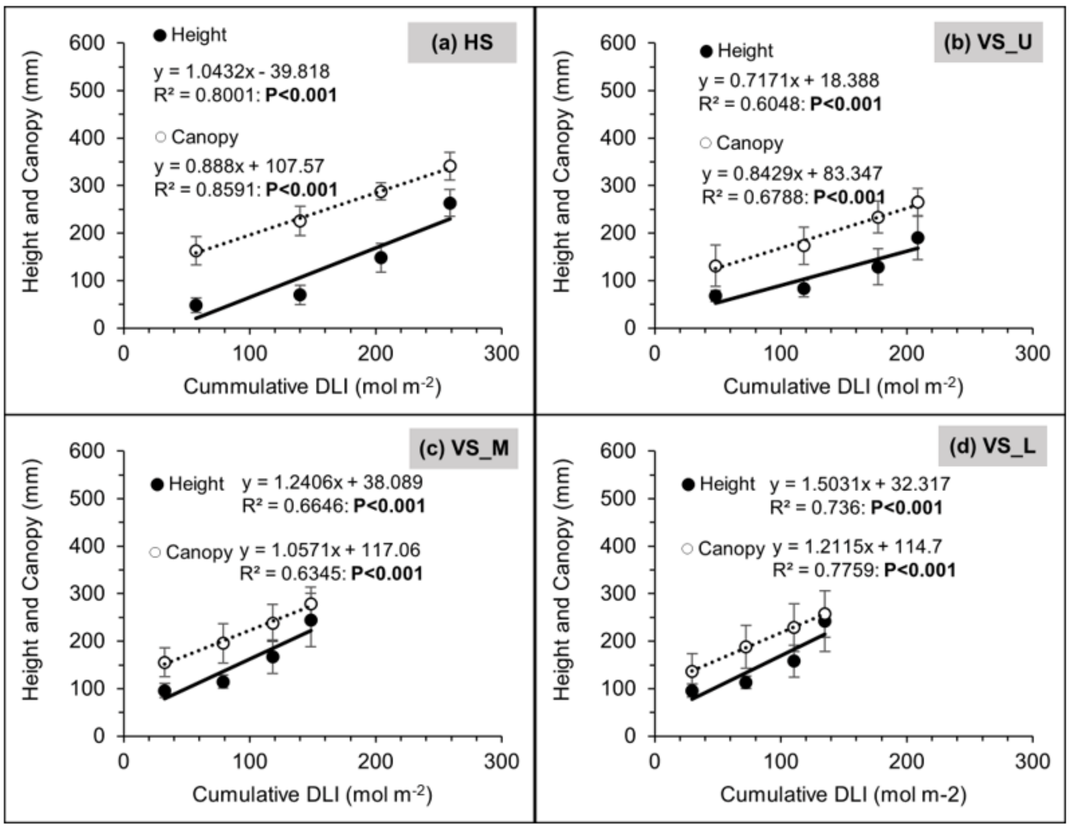

Figure 5. Relationships between lettuce 'Green Cos' (GC) growth and cumulative daily light integral (DLI) at four measurement times (at 7, 14, 21 and 28 d after transplanting). HS: Horizontal shelves; VS: vertical shelves; VS_U: vertical shelves at the upper level; VS_M: vertical shelves at the middle level; VS_L: vertical shelves at the lower level. Data points indicated means and error bars corresponded to the standard deviation.

When concerned on the water use efficiency (WUE), planting crops on the VS required 1.5 times more irrigation water than on HS in 1 m^2 (Table 3). This was due to higher plant density and lower FW and DW on VS than on HS. The total volume of irrigated water per shelf on VS was higher than on HS, with the values of HS = 0.43 m^3 per crop cycle and VS = 0.65 m^3 per crop cycle due to the higher plant density on VS in comparison to HS. Therefore, if the yields increase, the WUE will be also increased.

Table 3 shows the light use efficiency (LUE) calculated as the ratio of leaf FW to cumulative DLI (LUE_{FW}) and leaf DW to cumulative DLI (LUE_{DW}). The estimated LUE_{FW} and LUE_{DW} on VS (LUE_{FW} = 7.3 g mol^{-1} and LUE_{DW} = 0.46 g mol^{-1}) were 1.1 and 1.6 times more than on HS (LUE_{FW} = 6.7 g mol^{-1} and LUE_{DW} = 0.28 g mol^{-1}). This can be indicated that VS tended to transform light photons received by plants into biomass better than HS. However, the optimum light has to be managed to the plant, especially at the middle and lower levels of VS. The results from the study also pointed out that the reduction of DLI from upper to lower levels showed the differences between upper (9.1 mol m^{-2} d^{-1}) and middle (6.5 mol m^{-2} d^{-1}) levels as 29% and between upper and lower (5.9 mol m^{-2} d^{-1}) levels as 35%. The DW of lettuces decreased from upper to lower as well (Figure 2 and Table 2).

The shape of vertical shelves is the most important, for example, triangle or square shapes are directly related to the light absorbed by plants. Distances between shelves and the spaces within different levels at the same shelves can also create shading effect on plants because of higher shelves or plants covering the plants at the lower positions from the light supply as pointed out by Linsley-Noakes et al. (2004). Therefore, further investigation on the characteristics of shelves must be considered in terms of shape, size and distance. As mentioned in the study of Chaichana et al. (2022), the model was used to simulate the availability of sunlight in order to approximate the irradiation received by plants on the vertical shelves among different shelves and within the shelves.

In conclusion, the availability of sunshine was sufficient for lettuces growing on HS and VS at the top levels, but insufficient for lettuces growing on VS at the middle and lower levels. Even though, the fact that VS can yield more crops per unit area than HS, the light intensity must be adjusted properly to sustain plant growth. If the VS is to be used to produce higher yields, its vertical shape and distance must be taken into account. Additionally, VS can give an alternate farming technique for high-value crops or costly herbs, particularly in regions with fewer arable lands.

CONCLUSIONS

Different planting methods, horizontal shelves (HS) and vertical shelves (VS), had distinct effects on the growth and productivity of lettuce. Comparatively, lettuce grew and produced more abundantly on HS than on VS. Despite the fact that HS had much greater fresh and dry biomass than VS, VS can produce more crops per unit area. Therefore, VS utilized land more efficiently. Light is a limiting component for lettuce development and growth. Due to light availability, lettuce grew taller when it required greater light intensity. The lowest level of VS had the greatest height, but the lowest leaf fresh weight (FW) and dry weight (DW). The plant density of VS was 1.5 times that of HS. Moreover, growing crops on VS resulted in a larger crop per unit area, but light intensity must be adjusted to support plant growth in terms of the shape and arrangement of the shelves, including the spacing between shelves and the height from upper to lower levels. If the VS is to be utilized for crop cultivation in order to maximize yields per unit of vertical space, its vertical shape and distance between shelves and levels must be carefully evaluated for each crop.

Author contributions

Conceptualization: S.W., C.C. Methodology: S.W., N.K. Experiment and Data curation: S.W., T.P. Writing-original draft: S.W., N.K., N.W., T.P. Writing-review & editing: S.W., C.C. Project administration: C.C. Funding acquisition: C.C., N.W. All co-authors reviewed the final version and approved the manuscript before submission.

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